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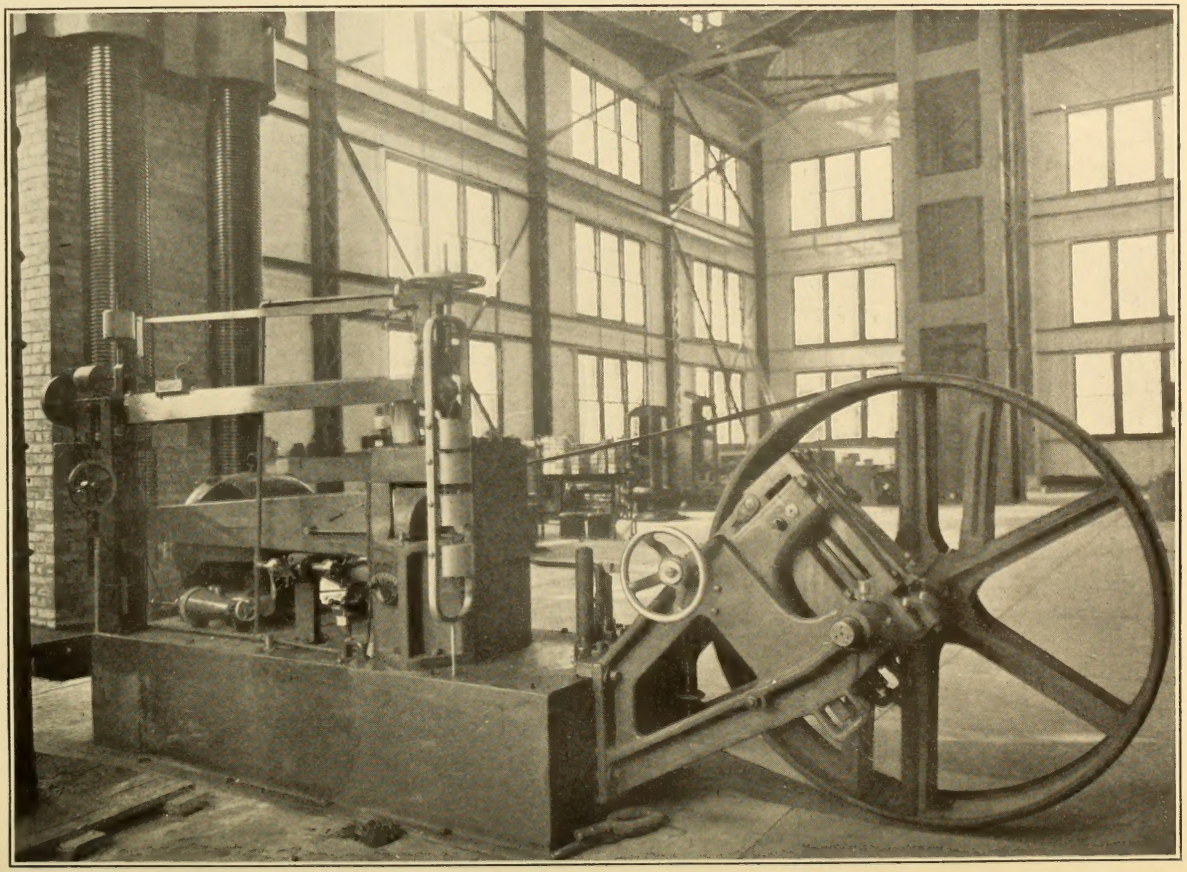

FIG. 1.—*View of weighing mechanism*

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DEPARTMENT OF COMMERCE

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OF THE

BUREAU OF STANDARDS

S. W. STRATTON, DIRECTOR

No. 101 ~ 108

TESTS OF LARGE BRIDGE COLUMNS

BY

J. H. GRIFFITH, Associate Engineer Physicist

and

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Bureau of Standards

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By J. H. Griffith and J. G. Bragg

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I. INTRODUCTION

1. GENERAL

There are recorded in the following pages the results of an experimental investigation on 18 large bridge columns conducted by the Bureau of Standards at Pittsburgh. The specimens tested represented compression members designed for three bridges of long spans recently erected. The linear dimensions of the specimens were one-half those of the corresponding bridge members. Two of the columns, the first to be tested, were of nickel steel. The originals were designed for the Municipal Bridge at St. Louis. Ten of the columns were for the Chicago, Burlington & Quincy Railroad bridge over the Ohio River at Metropolis, Ill. They were constructed of various alloy and high-carbon steels. The remaining six members, test specimens for the new Memphis Bridge at Memphis, Tenn., were of nickel alloy and carbon steels. They possessed several essential points of difference in design from the other members.

The primary purpose of the tests was to determine the strength of such members under intended axial loads in relation to their general design and the grades of steel used in their construction.

The secondary purpose was to study the distribution of stress and strain throughout the shafts of the columns and their different details.

In the majority of cases the columns tested were essentially studies in design. It was one of the main purposes of the consulting engineers engaged in the design and construction of the bridges to supplement their knowledge obtained from preliminary calculations with that found from determinations of maximum stresses in the columns and their respective details. It thus became possible for the engineers to introduce such later modifications in the final construction of the actual columns of the bridges as appeared desirable after study of the tests.

Certain observations have been carried out in detail for all the columns. The scheme of observations has been varied in certain details when such changes promised to give valuable information and seemed practicable.

The Bureau of Standards acknowledges the cooperation of various engineers and manufacturers in this work. The firm of Boller, Hodge & Baird, consulting engineers and designers of the Municipal Bridge, was represented by H. C. Baird, who was present during a portion of the time of testing of the nickel-steel columns. C. H. Cartlidge, bridge engineer of the Chicago, Burlington & Quincy Railroad, in charge of the design and construction of the Metropolis Bridge, and Ralph Modjeski, consulting engineer in the design and construction of the Memphis Bridge, both took an active interest in the investigation and were present at a number of the tests.

The American Bridge Co. and the Pennsylvania Steel Co. did much to make the investigation full and complete. C. E. G. Larsson, assistant chief engineer of the American Bridge Co., and Thomas Earle and C. H. Mercer, superintendent and chief engineer, respectively, of the Pennsylvania Steel Co., represented their companies on the work. The preliminary reports of these officials covering their respective interests in the investigation were kindly placed at the disposal of the Bureau. They were consulted in the preparation of this paper, especially in the checking of results with the independent calculations of the Bureau.

The writers wish to make personal acknowledgments to C. E. Chase and F. M. Masters, inspecting engineers for Ralph Modjeski; Edward Godfrey, chief engineer of R. W. Hunt Co., in charge of inspection of the Municipal Bridge columns; and to R. T. Leipold,

representing C. E. G. Larsson, for assistance in their various capacities in making strain measurements, recording, or in preparation of certain portions of the data on those columns in which they were directly interested. The suggestions and criticisms of H. S. Prichard and O. H. Basquin in interpreting and discussing data were valuable in several instances. Thanks are due to the American Bridge Co., through G. F. Sparhawk, engineer at the Ambridge plant, and to the photographer of the Pennsylvania Steel Co. for a number of the cuts shown.

2. DESCRIPTION OF APPARATUS

(*a*) *Testing Machine.*—The columns were tested in the 10 000 000-pound Olsen compression machine of the Bureau. To make clear certain later steps in the experimentation, a brief description of this machine will be given. Reference may be made to the construction and accessories as shown in Figs. 1 and 2. This machine is capable of testing specimens whose length does not exceed 25 feet and whose width in the clear does not exceed 6 feet. The upper head during a test remains stationary, but for the purpose of adjusting the machine to the length of the specimen this head is moved by large nuts turning on the 13½ inch screws of the testing machine. These nuts are actuated by a gearing mechanism directly connected to and independently operated by a 15-horsepower electric motor placed on the head. The lower platen rests on a spherical base of 5 feet radius, which is mounted upon a vertically acting piston of 50 inches diameter and 2 foot stroke. There is attached to the bottom of this piston a 14 inch by 2 foot 5 inch guiding plunger, which fits into the large base casting of the testing machine and serves for proper centering of the parts.

The lower or straining platen is subject to the oil pressure in the cylinder, which at the capacity of the machine is approximately 5000 pounds per square inch. The oil pressure communicates through auxiliary piping with a smaller piston of $5\frac{9}{16}$ inches diameter. This piston has a "knife-edge" bearing on the main lever of an Olsen lever system. The ratio of the areas of the large and small piston is approximately 80:1, so that about 1/80 of the pressure upon the specimen is weighed, the weighing lever being graduated to read the actual load on the column.

The method of operating the machine during the tests was as follows: A triple plunger pump (see Fig. 1), having an air dome

FIG. 2.—*Bureau of Standards, 10 000 000 pound testing machine. Column 32S (silicon steel) under test*

for equalizing the pulsations of the three pistons and actuated by a 15-horsepower intrapole motor, is set in motion, the main valve of the mechanism being open and the relief valve closed. The function of the relief valve is to "short-circuit" the oil into the rectangular reservoir shown beneath the weighing mechanism. Speeds of the lower platen are varied in the following manner: Either by varying the lengths of strokes of pump piston through the hand wheel; by closing a by-pass needle valve and permitting only small quantities of oil to pass through into the main cylinder; or by varying the operating speed of the motor through the controller switch. The speeds of the main piston may in this manner be changed from 1/60 to 1/2 inch per minute.

For the purpose of uniformity in the application of loads, substantially the same piston speed was used in all tests. After the maximum load was recorded the column was strained at a higher speed in a manner to exaggerate its type of failure and the form of the deflection curve.

In reading the extensometers some 10 or 15 minutes were usually required by a single observer to take the strain measurements. In the earlier work the machine was stopped and held at the load with but little falling off. On a number of the later columns, however, as the time for observation was approached, the slowest possible speed was applied by means of the needle valve. The observer endeavored to so time his observation by beginning a few thousand pounds before and ending an equal interval later than the time at which the recorded load was reached that the mean time for the observations was the same as that of the recorded load. It is thought either of these methods gave satisfactory results.

(*b*) *Preparation for Tests.*—In preparing for a test the lower platen was leveled, the pin bearing was accurately centered on the platen, and the column was placed on the pin bearing by means of an overhead crane. The platen was lifted by applying pressure through the pump and tilted until a close parallelism of the upper column face was secured with the top head of the machine. The column was brought to bear in uniform contact with the upper head by such further adjustments of the lower platen as were found to be necessary.

The machine was "balanced" with the scale beam poise at zero, while there was an upward motion of the column during the working of the pump and before contact of the column with the upper head of testing machine was effected. This was done to eliminate

friction of the large piston as far as possible by substituting dynamic for static friction. With one exception, the initial load was taken at 1000 pounds per square inch of column cross section. Below loads of about this value stress strain readings are commonly found to be erratic, probably owing to nonuniform bearing in the testing machine. The loads applied were such as to give increments of stress of multiples of 1000 pounds per square inch. The strain readings were taken generally at closer intervals in the vicinity of the column yield point.

(*c*) *Calibration and Accuracy of the Testing Machine.*—On account of the capacity of the machine, the methods commonly used in calibration were impracticable, and the special apparatus for calibration was not finished at the time of tests. It was decided to use the test columns themselves as calibrating members, the method essentially being to compare the moduli of the columns with that of the mean moduli for steel as deduced from independent tests made on steel columns and small specimens. The mean axial modulus for the columns was found to be 29 600 000 pounds per square inch, with a probable error of the mean of $\pm$120 000 pounds per square inch. This modulus is in close agreement with the mean modulus for steel as given from independent sources. The data and methods of calculation are fully described in the discussion in Part IV. Independent calibrations of this machine will be made later and the results published. It is believed that if any error exists in the constant of the machine, it is well within 1 per cent, judging from the values found in other large column tests.

3. PURPOSE AND SCOPE OF THE INVESTIGATION

(*a*) *Column Strain in General.*—It is recognized in the Mechanics of Materials [1] that there are but two determinate conditions under which a member in a testing machine may be tested: (1) Under such condition as will permit full freedom of motion at the ends, so that the column may accommodate itself to whatever flexure or unequal stress distributions occur during loading. Knife-edge bearings or ball joints have been used for this purpose in a number of tests. (2) Under the conditions where the bearings are fully restrained so that the terminal slopes of the strained axis may be maintained constant at that perpendicularity to the testing machine platens which existed before loading.

[1] Johnson's "Materials of Construction," 4th ed., p. 361.

If the terminal conditions are not definite, more or less indetermination is introduced in the mechanical status of the strained members.[2] This exists to a greater or less extent in the common type of end conditions where the members simply rest against the platens, however true the parallelism of end surfaces to platens may be. The volume of pressure (or surface integral) on the ends is indefinite, except as to the magnitude of its resultant. The shearing and normal stresses on the end surfaces cause bending and twisting of the column. These stresses are largely indeterminate experimentally with respect to their intensities and laws of variation. Moreover, the platens of the most perfectly constructed testing machines experience some elastic and inelastic displacements. When the column is otherwise mechanically defined as to its setting in the testing machine and its physical properties and coefficients as required in elastic analyses are known, it is believed the difference between the results actually obtained by tests and those that are deduced theoretically may still be sufficient by reason of the uncertainties enumerated to account for some of the discrepancies which are found to occur between theoretical and practical experimental determinations. The problem at hand is a practical one—to obtain the best possible results from the data by methods commonly employed among engineers, taking due account of such indetermination as exists as far as may be practicable, and keeping consistently in mind the general status of strain in the formation of judgments and the determination of laws.[3]

Although engineers have given various interesting analyses of those cases in which the variable tangent planes to the strained axis in general fall outside the principal planes of flexure, practical expediency makes it desirable to omit the consideration of a twisting torque, if its influence is sufficiently small that it may be neglected, and this was done with the following justifications. The columns are designed in such an ample manner that the twists which will occur in a more flexible member become relatively important. Evidence of this is shown in the cuts after failure. The deflection curves were always confined to one or the other of the principal planes for all the columns except those of nickel steel, and in these two the slight twists were purely

[2] See discussion of Ernest Jonson, Trans. A. S. C. E., 61, p. 200.

[3] J. O. Eckersley, in a parallel scheme, has shown the relation of the more rigorous theory of columns to the practical engineering theory. Trans. A. S. C. E., 76, p. 280. Love's Theory of Elasticity (2d ed., Cambridge, 1906), p. 370, gives an extended discussion of the equations of equilibrium which are to be satisfied as stated by Clebsch, Kirchhoff, and others. Reference may be made to Burr's Elasticity and Resistance of Materials, p. 447 et seq., for the engineering theory of the column, which has mainly been followed in this discussion.

local phenomena rather than actions of the members as a whole. These plane deflection curves were also always found in the tests of a long series of smaller columns conducted before the work of the present investigation was taken up. With the above distinctions in mind, the analysis of results has been conducted mainly from the more common engineering viewpoint. An effort has been made to state what appears to be the law of action of these columns in a way sufficient to meet the practical needs of designers in estimating the strengths of columns whose construction is similar to those discussed.

(*b*) *End Conditions.*—Column U_8U_9 of nickel steel had two square ends, the pin being omitted. Each of the others had a square upper end and a pin bearing at the lower end. The lower platform rests on a spherical surface of 5-foot radius, as has been described. Since the radius of curvature of the spherical bearing is relatively much greater than the radius of the pin, due account being taken of the coefficients of friction, motion must occur at the pin as the column deflects if it occurs at all. It seems, therefore, in the main proper to consider that the lower end of the columns, as is quite evident from the latter data, behaves practically as an ordinary square bearing up to a point near failure, when the friction is gradually overcome and the columns take the theoretical plane deflection curve corresponding to a pin and square ended member. (See Fig. 47.) When deflection takes place in the plane of axes of pin and column there is a reasonable "square-ended" restraint to the member. (See Fig. 50.)

(*c*) *Selection of Observation Stations—Extensometers.*—In view of the essentially heterogeneous nature of the steel it was deemed more appropriate to discuss, as a rule, the strain deportment of the members and details instead of their behavior in terms of stress, for the reason that the fundamental quantities directly measured are displacements and deformations. Although many engineers have expressed their experimental results in terms of stress, this seems inappropriate in the present analysis because stress as usually experimentally determined is a derivative quantity, obtained by multiplying the mean strain (deformation per inch of length), as measured with extensometers, by moduli of the material.

To observe the action of the members as a whole without special reference to the local distortions, which are always present to a greater or less extent in "built-up" columns, wooden rod extensometers were placed on the external flange angles, these being

placed symmetrically with reference to the mid length of the columns.[4] These extensometers were 80 inches long, having a gauge length conveniently taken as 5 and 10 multiples of that for the Berry portable gauges to be described later.[5] They had ball-joint connections at the top. At the bottom, through the medium of a sharp conical bearing, the rods rested on the spindles of Ames's dials. To prevent lost motion in these extensometers the spindles were held against the rods with rubber bands. The dial and ball-joint attachments were rigidly connected to small steel bars which screwed into ¼-inch tapped holes in the column. The Ames's dials read to 0.001 inch directly and by estimation to 0.0001 inch, the maximum error usually not exceeding 0.0002 or 0.0003 inch, as determined by the calibration. This error is insignificant in the platting of stress-strain curves. The common theory indicates that the extensometers should be placed symmetrically about the lower third point of the columns, so as to cover the commonly assumed region of greatest flexure, but, as has already been remarked, since the friction of the pin constrains the member for a considerable range of loading closely to its original perpendicularity with the base, it was deemed more justifiable to take readings at the mid-point, as has been described. The 20-inch Howard gauge was used on U_2U_3 and U_8U_9 for readings at the middle of column instead of 80-inch extensometers. The 8 or 16 inch Berry gauge was used for the remaining readings of these members and the other columns.

The outline of instructions for testing of the columns of the American Society of Civil Engineers' committee,[6] which was issued some time after this investigation was begun, recommended that four long-length gauge readings be taken on each member tested, two on the corners and one on the center of the flange and one on the center of the web. A departure from this suggestion was made for the purpose of having symmetry of observation stations about the axis, so that in all cases the mean axial strain could be found, special emphasis in this investigation being laid on the determination of axial moduli and stress-strain curves for a comparative study of behaviors of the various members.

Readings in 8-inch and 16-inch gauge lengths were taken in the majority of cases at the mid-lengths on the webs and flanges and at the ends, but sufficiently removed from pin plates and end

[4] The coefficient of expansion of wood is lower than in steel, but hygrometric effects are important when rods are not varnished.

[5] Longer lengths than 80 to 100 inches were found from previous investigations to be not as reliable in obtaining sets as the lengths chosen.

[6] Proc. Am. Soc. of Civil Engs., Jan. 20, 1915.

battens to avoid local effects due to the absorption of stress from the pin into the body of the column. Transverse readings in close proximity to the longitudinal stations were taken in a sufficient number of cases to determine the ratio of lateral to longitudinal strain; i. e., Poisson's ratio.

The Berry portable strain gauge was used for the shorter gauge readings. This gauge has "invar" steel side strips, the coefficient of expansion of this steel being nominally only about one-twenty-eighth that of carbon steel (but sometimes varying from this), so that it is affected little in handling. There is a fixed point at one end and a movable joint and bell-crank lever at the other end, the arm of this crank being connected to an Ame's gauge spindle, giving the possibility of reading directly to 0.0002 inch through the 1:5 multiplication of the bell-crank lever, and by estimation to 0.00002 inch. Two holes were drilled 8 inches apart, with a No. 55 drill, for setting the gauge. The holes were countersunk with a tool having an angle of 110 degrees, for the purpose of insuring a good shoulder in setting the gauge points.

The 8-inch Berry gauge was calibrated by means of an accurately machined apparatus consisting of fixed and movable steel heads mounted upon a substantial base. The gauge points were inserted in holes in the heads similar to those made with the No. 55 drill in the columns. The gauge was clamped in position by a "C" clamp similar to that used in clamping the instrument to a test piece. Small displacements of the movable head were measured with a screw micrometer attached to the apparatus and the corresponding readings on the dial taken. The micrometer read by vernier to 0.0001 inch, and its error was found by independent calibrations to be always less than 0.0001 inch for travel of the screw in either direction. The constant of the 8-inch gauge was found after a number of trials to be 0.956. The constants of 2-inch and 10-inch gauges were found to be 0.946 and 0.950, respectively. These values may be in error by one or two units in the last figure in each case. Observations made with the standard bar accompanying the gauges show that an observer can usually check his readings to within 0.0001 or 0.0002 inch. The chief sources of errors in the Berry gauge readings of the present tests may be attributed to imperfect holes for placing the gauge points. These holes are inserted with a portable drill and their axes are not always precisely normal to the surface of the column at the point measurements are taken. The gauges have been chiefly employed in the

tests for obtaining the behavior of the column details qualitatively. The results determined in this way may be in error to the extent of ± 5 or 10 per cent. Where quantitative results are desired for the purpose of making a closer comparison, the strains have been multiplied by 0.956 in the later discussions of the results.

The Ames' dials were found by similar calibrations, as a rule, to give readings correct within 0.0002 or 0.0003 inch. In certain dials it was observed that the reading at a particular point of the graduated arc may be at times as high as 0.0010 inch. The errors of the dials are largely compensated by the method of averaging results which was employed in the discussion of the observations.

(*d*) *Pin-Plate Observations.*—It was the original intention of the experimenters to determine data for platting the direction of the resultant strain and "lines of stress" in the flow of these from the pin, this being a "source" of strain energy from the lower platform, as the member is compressed. On account of the effects of initial strain, apparent lost motion and distortions of the plates themselves, it was difficult to draw precise conclusions in this respect. More attention was then given to a study of the amount of slip in the plates themselves, which is an important factor to be determined.

(*e*) *Lattice-Bar Observations.*—Two types of lattice bars are presented for discussion. One is the ordinary type in which double and single diagonal bars are used. The other employs in addition to the double diagonal members of the lattice panels a transverse bar between successive panels. This style of lattice will be of interest to engineers, because it was used throughout in the Hoangho Bridge[7] recently erected in the Province of Kaow Chow, China. The system is deserving of study in America as to certain possible mechanical advantages.[8] A sufficient study has been given to the two types to afford opportunities for comparison and the formation of judgments.

(*f*) *Repetitions of Load—Initial Strain.*—Attention is called to some behaviors obtained when various repetitions of the load were applied within the yield point of the column. The effect upon the various details, especially pin plates and lattice bars, is interesting and is indicated by the successive stress-strain curves.

The initial strain in columns has been discussed and supplementary tests have been given to show the influence of strains induced through fabrication operations.

[7] Die Hoangho-Brücke, Zeit. des Vereines Deutscher Ingenieure, 58, pp. 374–377, Mar. 7, 1914.

[8] A rather slender and ineffective type of this lattice was used also on the first Quebec Bridge members.

(*g*) *Deflections.*—A number of measurements for deflection were taken in the coordinate directions parallel and perpendicular to the pin on columns U_2U_3 and U_8U_9 at the mid lengths. The results of these measurements are given to afford some idea of the local strains and twists to which the columns were subject. The method, however, is open to some criticism, it is believed, in the case of absolute deflections and was abandoned on the later columns. In several of the other columns a taut thin wire was stretched between points at the top and bottom. It has been remarked, however, by Buchanan [9] with reference to his own tests that "the deflection movements lateral and vertical were so irregular and eccentric that they were not thought to have any particular significance in determining the elastic value of the column" and perhaps the importance of the deflection has been overrated by those who are inclined to take the purely mathematical viewpoint in establishing a mechanics of the built-up member of small slenderness ratio.

(*h*) *Analysis of Data.*—In analyses of the experimental strain data of columns, engineers are often perplexed on account of the fact that while the platted results of calculation call for smooth curves without discontinuities, the experimental curves of laboratory practice are too often made up of many "zigzags" and tacks. This may be seen, for example, in a study of the numerous diagrams given by Talbot and Moore [10] in their investigation of built-up columns, or is instanced in the remark of Buchanan on the irregularity of the laws of column deflections obtained by him. It is quite inevitable that this must often be the case in any single analysis of a built-up member, even when the effect of minor variables have been taken into account and there has been an adequate compensation for accidental errors. An individual test is usually insufficient for the determination of correct conclusions on account of local action and readjustment in the pieces when strained. A recourse rather must be had to what Maxwell and Gibbs have called statistical methods in the interpretation of results. It is the general trend of the data that is of most importance and not the conclusion from a particular test in deriving laws of behavior. In the analysis of results given by the authors attention has been directed chiefly to determining the laws of the series of columns, rather than to those of individual cases. Comparisons of the stress-strain curves drawn for par-

[9] Engineering News, 58, p. 685; Dec. 26, 1907.

[10] Talbot and Moore, Investigation of Built-Up Columns Under Load, Univ. Ill. Exp. Station, Bull. 44, Figs. 8–15, p. 22 et seq.; also summary.

ticular stations of a column with the mean curves afford interesting data. To give all these curves, however, would extend the scope of the paper beyond the limits planned. Reference may be made to the tables for much matter bearing upon the behavior of individual columns for which time and space do not permit a discussion.

II. ORIGINAL DATA OF THE INVESTIGATION

1. DESCRIPTION OF TEST COLUMNS

There were seven distinct types of columns presented for test. In certain cases the design and dimensions of the columns were unvaried, but different grades of steel have been used in the construction, the steel being considered the essential variable. In other cases the designs and steels were both varied in accordance with the judgment of the designers, in such a way as to give the best performance as columns when the cost of construction was considered. The subdivision of the group was as follows (see Table 1): There were two columns of 3¼ per cent nickel steel, but of different dimensions corresponding to two separate members in the Municipal Bridge. There was but one member under consideration for the Metropolis Bridge. Two separate designs of this member were made and five grades of steel were used in the construction, viz, Mayari (1½ per cent nickel alloy from natural Cuban ore), silicon, chrome, and two grades of high-carbon steel, making 10 test members. In the case of the Memphis Bridge 3 different members of the bridge were considered. There were two designs corresponding to each of the originals, one for the use of high-carbon steel and the other for the Mayari steel, making 6 test members.

Table 1 gives the physical dimensions of the test columns, the different types of cross sections and their areas, the values of the radii of gyration and slenderness ratios used by the designers, with other essential data. The areas used by the designers were calculated from tables in the steel handbook and are recorded under the heading "Nominal area." They were used in calculating the total and unit loads at which observations were made. (See Tables 3 to 21.) After the completion of the experimentation, it was found that the scale weights of the different plates and angles used in the column shafts were available through the courtesy of the steel companies for most of the columns. The exact areas were calculated from these weights and are given under the heading "Actual areas." They were used in correcting the maximum stresses and moduli of the columns given in the discussion of Part IV.

2. CHEMICAL AND PHYSICAL TESTS

The chemical and physical properties of the steels used in the construction of the columns are given in Table 2. These are later discussed in connection with the behaviors of the columns.

III. RESULTS OF TESTS

1. DESCRIPTION OF TABLES AND CURVES

In Tables 3 to 21, inclusive, the numerals at the nead of the columns give the station numbers at which strain readings were taken. A key to the position of these stations is found by reference to similar numerals placed upon diagrammatic sketches of the essential portion of the columns. One of these accompanies each table.

The initial-strain readings are taken, for reasons previously mentioned, at a load of 1000 pounds per square inch, which serves as the zero of the observations. Unusual care is required in taking the initial set of observations. Attention is drawn to a few results in the tables by footnote explanation where an error in the initial readings seemed probable.

The tabulated data given under the station numerals represent the cumulative positive or negative elongations in the gauge lengths between extensometer points corresponding to the load recorded by the beam of the testing machine. The plus sign (+) denotes extension in the steel; minus (−) denotes compression. These data are immediately derived from the original log sheets by taking the differences of initial and later readings of the extensometer dials at the particular loads under consideration. The results were finally checked with the original readings as recorded.[11] The strain data given in the table will suffice for many purposes in studying the behavior of columns under load. To make some of this information more readily apparent, stress-strain curves have been platted in a large number of instances, as shown in Figs. 22 to 41.

In the curves which show the action of the column as a whole the relative elongations in 80 inches, found by averaging readings

[11] It is common among observers to correct for considerable changes in temperature by compensating all readings with reference to a standard bar reading taken at the beginning and end of the interval of a series of observations. In the earlier experimentation time, temperature, and standard bar readings were taken for each load, but from practical considerations this was later abandoned, as the small variation in the surface temperature warranted the inference that the temperature within the body of column was uniform in the time range of test. In view of the fact that the probable error in a reading of the dial may be perhaps ±0.0001 inch or 0.0002 inch, no increase in accuracy attaches to a compensation of the results when the small range of temperature is considered, and the corrections being close to the above amounts, a slight error may even be introduced. Special attention was given to maintaining the temperature of the room nearly constant so that the variation of the mean temperature of the members was probably less than 1 degree in all cases.

at stations 1 to 4 and dividing by 80, are platted with the stresses. The slope of the resulting curve gives the mean modulus of the column. This modulus becomes variable and loses its ordinary meaning at a critical stress equal to approximately half the maximum load per square inch on the column. The critical point at which deviation of the curve from the tangent at the origin takes place has been called in this paper the proportional limit of the column by analogy with that found for a small test piece. It is, of course, understood that the proportional limit as above defined is not that of the component steel. It may be called that of the fabricated material. Readings have been reduced to strains and averaged, and stress-strain curves are platted in a number of cases for 8-inch gauge lengths at the middle of columns and adjacent to pin plates. While these curves are quite similar in form to the preceding, a slight difference in slope may in general be expected and is probably influenced by the lack of uniformity of stress distribution to some extent, also by the variable degrees in "fluting" or "waviness" of the different shapes brought about by the clamping action of high-power riveters.

The writers were unable to devise a very efficient graphical method for showing systematically the variation of strains in the latticing. This can be studied most expeditiously by direct observation and comparison of the elongations ($\pm$) as given in the table themselves for any group of lattice bars. The behaviors that are taking place are very apparent and easily analyzed. In Figs. 28 and 35 the axial strains in lattice bars are shown as functions of the average stress on the columns.

Curves have been drawn to illustrate the slipping of one pin plate over another. (See Figs. 26, 27, etc.) The principle involved consists in taking two gauge readings side by side for comparison as was done, for example, on column 31HC in Table 8 and Fig. 26. One gauge point was placed at the end of the lower outer pin plate. Another was placed on the plate next in order and on the same line as the first, but about one-half inch removed. Two other gauge points were similarly placed 16 inches away from the first. The horizontal difference between the abscissas of curves gives the relative movement of one plate over the other per inch of gauge length. The actual displacements are shown by the abscissas of the resultant curve multiplied by 16. Further evidence that this slip actually occurred was found by placing the fingers on the lower end of certain columns where

the movement was pronounced. The original planed surface at initial loading became "stepped" in some cases at an earlier stage than in others, the serrated action gradually increasing with the load. (See Fig. 43.)

In some cases scaling of the column was noted in proximity to the elastic limit of the steel and is recorded. In most cases but one maximum load was found, but in others, noticeably column MY, Table 7, after the column appreciably deflected higher loads were obtained with further deflections until a *maximum maximorum* was reached at some 4000 pounds per square inch higher than that of the primary failure.

The four columns US_2 MS_1 and U_2M_1 failed prematurely by sudden bending at the lower end for obvious reasons, and did not develop the full strength of their sections. Evidences of readjustments taking place as the loads advanced were apparent in many of the columns and have been recorded as "creaking sounds."

Systematic observations were made for deflections in the two coordinate directions of the cross section on columns U_2U_3 and U_8U_9. The apparatus used is illustrated in Fig. 5. The measurements were made at stations indicated with a B. & S. screw micrometer, and were read to 0.001 inch. The component displacements calculated from the data are given in Table 5. The plus sign signified an outward movement from the original axis. In the case of the other columns the measurements of deflections were made at the mid lengths of each column. A rule and taut wire attached to the ends of columns were used for this purpose.

2. EXPLANATORY NOTE ON TABLES AND CURVES

The following recapitulatory explanation will be found useful in a cursory examination of the data derived from the experiments.

Table 1 gives the structural and mechanical data for each column, its location in the bridge, etc.

Table 2 gives the results of chemical analyses and physical tests for the different steels used in the construction of columns.

Tables 3 to 21 give the cumulative deformations determined at the various stations of observation corresponding to the applied stresses in pounds per square inch of sectional area of the columns. Figs. 22 to 41, inclusive, show stress-strain curves platted from these data.

Remarks.—(*a*) Order: The tabular data, stress-strain curves, and photographs of members after failure follow the order of Table 1 throughout.

(*b*) Stations: The stations of observation are indicated by the numerals over the tabular data. The position and orientation of these stations on the respective members are given on the diagramatic or key sketch accompanying each table, Figs. 3 to 21, inclusive.

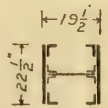
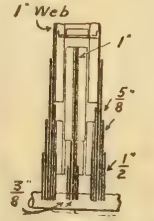
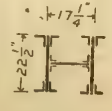
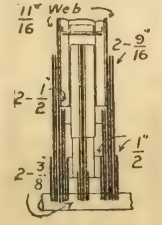
(*c*) Readings: The initial load as measured on the testing machine, unless noted, corresponds to 1000 pounds per square of nominal area of column. (See Table 1.) The increments of loading are taken in multiples of 1000 pounds per square inch of nominal section. The values recorded in the tables are the cumulative deformations in inches found by subtracting the reading on the extensometer at inital load from that at any load under consideration. The sign (+) signifies an elongation in the steel; (—) a contraction. The deformation recorded is the mean amount observed in whatever gauge length was used, 8 to 16 inches or 80 inches, as it happens to be.

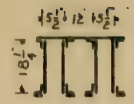
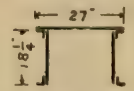
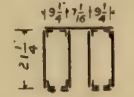
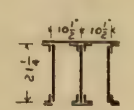
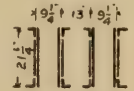
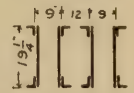
(*d*) Curves: To place all strain measurements on a mechanical parity for the group of columns, the deformations per inch—i. e., the mean strains—were calculated. To obtain these the tabular values are divided by the respective gauge legths, 8 to 16 inches or 80 inches, as the case may be. In the curves of Figs. 22 to 41, these mean strains are platted as abscissas; the mean stresses per square inch nominal area of column cross section are platted as ordinates. Other data are given on the figures themselves.

(*e*) The modulus of a column is taken (within the limits of proportionality) as the ratio of the mean stress over its cross section to the average strain as found from the readings upon the four 80-inch extensometers placed at mid length of the column and parallel to its axis. The "Proportional limit" for the column was taken as the stress at which there was a sensible deviation from constant proportionality of stress to strain. as shown by the 80-inch gauge lengths. Its value is about half the tensile yield stress of the column material as determined in the ordinary manner. The maximum loads, moduli, etc., given in Fig. 60 have been corrected to correspond with exact cross-sectional areas determined by weighing the columns, the results differing but slightly from those deduced from the nominal areas as found from the pocket-book shapes.

For further explanations, reference should be made to the descriptions and studies given in the paper, and to the figures and tables themselves.

TABLE 1.—Structural and Mechanical Data Concerning Columns Tested

Bridge	Name of column	Steel	Manuf.	"L" length of column, center of pin to upper end.	Ends: Diam. of lower pin, in.	Ends: Upper	Cross section of shaft	Material of shaft	Material at pin end	Bracing of shaft: Lattice, in.	Bracing of shaft: Transv. diaphgms, in.	Bracing of shaft: Battens at pin, in.	Area, sq. in.: Nominal	Area, sq. in.: Actual	Radius of gyration R: ⊥ to pin	Radius of gyration R: ∥ to pin	Slenderness ratio = L÷R: ⊥ to pin	Slenderness ratio = L÷R: ∥ to pin
Municipal, St. Louis	U_2U_2	Ni	American Bridge Co.	15 ft. 8½ in. end top chord	7½	Square		2 out. webs, 24″x$\frac{3}{4}$″ 4 out. Ls, 4″x4″x$\frac{7}{16}$″ 1 cen. web, 24″x$\frac{1}{16}$″ 4 cen. Ls, 4″x4″x$\frac{6}{16}$″ 2 dia. pls. 9½″x$\frac{6}{16}$″ 8 dia. Ls, 2″x2″x$\frac{1}{4}$″	In order from outside for U_2U_3 only 6 pls. $\frac{7}{16}$″ thick 2 pls. $\frac{1}{2}$″ thick 2 pls. $\frac{7}{16}$″ thick 2 webs, $\frac{3}{4}$″ thick out. 2 pls. $\frac{1}{2}$″ thick 8 pls. $\frac{3}{8}$″ thick 1 cen. web, $\frac{1}{16}$″ thick	2½ chan. ($\frac{1}{4}$ web)	3 $\frac{1}{4}$ thick	$\frac{1}{4}$ pls.	88.8	no data	7.55	8.57	25.0	22.0
	U_3U_3	Ni		24 ft. 0 in. center top chord	Square Pin not used			2 out. webs, 24″x$\frac{3}{4}$″ 2 side pls. 16″x$\frac{7}{16}$″ 4 out. Ls, 4″x4″x$\frac{7}{16}$″ 1 cen. web, 24″x$\frac{1}{16}$″ 4 cen. Ls, 4″x4″x$\frac{6}{16}$″ 2 dia. pls. 9½″x$\frac{6}{16}$″ 8 dia. Ls, 2″x2″x$\frac{1}{4}$″			3 $\frac{5}{16}$ thick	$\frac{1}{4}$ pls.	110.3	no data	7.78	8.97	37.0	32.1
Metropolis	HC	C	Penna. Steel Co.	All 24 ft. 4 in. upper end post	7	Square		2 side pls. 22½″x1″ 4 Ls, 4″x4″x$\frac{1}{2}$″ 1 dia. pl. 17½″x$\frac{7}{16}$″ 4 dia. Ls, 3″x3″x$\frac{3}{8}$″		Transv. 4x3x$\frac{6}{16}$ in. angles diag. 4x$\frac{1}{4}$ bars	3 $\frac{1}{4}$ thick	$\frac{1}{4}$ pls.	76.14	74.58	6.73	8.46 for all	43.5	34.5
	MY	My											76.14	74.90				
	31HC	C	Amer. Bridge Co.										75.99	76.94				
	32S	Si											75.99	76.94				
	34CS	Cr											75.99	76.94				
	HC1	C	Penna. Steel Co.	All 24 ft. 4 in. upper end post	7	Square		2 side pls. 22⅞″x1$\frac{1}{16}$″ 8 Ls, 4″x4″x$\frac{1}{2}$″ 1 dia. pl. 15$\frac{3}{4}$″x$\frac{7}{16}$″ 4 Ls, 3″x3″x$\frac{3}{8}$″		Transv. 4x3x$\frac{6}{16}$ angles diag. 3x$\frac{1}{4}$ bars	3 $\frac{1}{4}$ thick	$\frac{1}{4}$ pls.	76.46	75.35	7.60	8.05 for all	38.5	36.4
	MY1	My											76.46	75.28				
	31HC1	C	Amer. Bridge Co.										76.26	77.17				
	32S1	Si											76.26	77.17				
	34CS1	Cr											76.26	77.17				

Memphis	US_2MS_1	C	Penna. Steel Co.	15 ft. 10 in. upper end post	7	Square		1 cov. pl. 27″x$\frac{1}{2}$″ 4 web pls. 18″x$\frac{7}{16}$″ 8 Ls, 3″x2″x$\frac{5}{16}$″ 4 flats, 2″x$\frac{5}{16}$″	Each col. rib: 1 pl. $\frac{1}{2}$″ outside 1 pl. $\frac{5}{16}$″ inside 1 web, $\frac{7}{16}$″	Transv. tie pls. $\frac{1}{4}$, see cuts; diag. bar 3x$\frac{1}{4}$	$\frac{4}{1}$ thick	$\frac{7}{16}$ pl.	55.17	55.97	6.61	9.05	28.7	21.0
	US_2MS_1	My		15 ft. 10 in. upper end post				1 cov. pl. 27″x$\frac{7}{16}$″ 2 web pls. 18″x$\frac{1}{2}$″ 6 Ls, 3″x3″x$\frac{5}{16}$″	Each col. rib: 2 pls. $\frac{9}{16}$″ outside 2 pls. $\frac{5}{16}$″ inside 1 web pl. $\frac{1}{2}$″	Diags. 3x1$\frac{3}{4}$x$\frac{1}{4}$ angles	None	$\frac{3}{8}$ pl.	42.47	41.66	6.87	9.78	27.7	19.4
	U_2M_1	C		23 ft. 6 in. upper end post	8½			1 cov. pl. 25″x$\frac{1}{2}$″ 4 web pls. 21″x$\frac{11}{16}$″ 8 Ls, 4″x3″x$\frac{1}{2}$″ 4 flats, 3″x$\frac{1}{2}$″	Each col. rib: 1 pl. $\frac{1}{2}$″ outside 1 pl. $\frac{1}{2}$″ inside 1 pl. $\frac{5}{16}$″ inside 1 web, $\frac{11}{16}$″	Diags. 3x1$\frac{3}{4}$x$\frac{1}{4}$ angles	6 $\frac{1}{4}$ thick	$\frac{7}{16}$ pl.	96.01	95.77	7.80	9.25	36.1	30.5
	U_2M_1	My		23 ft. 6 in. upper end post				1 cov. pl. 27″x$\frac{1}{2}$″ 2 out. webs, 21″x$\frac{11}{32}$″ 4 out. Ls, 4″x3″x$\frac{1}{2}$″ 2 flats, 3″x$\frac{3}{8}$″ 1 cen. web. 21″x$\frac{11}{16}$″ 4 cen. Ls, 4″x3″x$\frac{3}{8}$″ 1 flat, 6½″x$\frac{3}{8}$″	Outside ribs (2): 2 pls. $\frac{1}{2}$″ 2 pls. $\frac{5}{16}$″ 2pls. $\frac{3}{16}$″ 2 pls. $\frac{3}{8}$″ } Cen. rib (1) 2 pls. $\frac{9}{16}$″	Diags. 3x1$\frac{3}{4}$x$\frac{1}{4}$ angles	5 $\frac{1}{4}$ thick	$\frac{7}{16}$ pl.	66.55	66.02	8.17	8.47	34.5	33.8
	LC_6LC_1	C		15 ft. 6 in. bot. chord at pier				4 webs, 21″x$\frac{3}{8}$″ 4 side pls. 13″x$\frac{1}{2}$″ 8 Ls, 4″x4″x$\frac{1}{2}$″	Each col. rib: 3 pls. $\frac{3}{8}$″ 1 web, $\frac{3}{4}$″ 1 side pl. $\frac{1}{2}$″	Tie pls. $\frac{1}{4}$ diag. 3x1$\frac{3}{4}$x$\frac{1}{4}$ angles	$\frac{4}{1}$ thick	$\frac{7}{16}$ pls.	119.00	118.18	6.74	12.14	27.6	15.3
	LC_6LC_1	My		15 ft. 6 in. bot. chord at pier				4 webs, 19″x$\frac{11}{16}$″ 8 Ls, 4″x4″x$\frac{1}{2}$″	Each col. rib: 3 pls. $\frac{3}{8}$″ 1 pl. $\frac{1}{2}$″ 1 web pl. $\frac{11}{16}$″	Tie pls. $\frac{1}{4}$ diag. 3x1$\frac{3}{4}$x$\frac{1}{4}$ angles	$\frac{4}{1}$ thick	$\frac{7}{16}$ pls.	75.12	76.47	6.87	11.59	27.1	16.0

Notes on rivets; The batten plates, lattice bars, and transverse diaphragms of columns U_2 U_3 and U_8 U_9 were of carbon steel, the other material being of nickel steel. All of this material was subpunched and reamed. The rivets in the main members were nickel steel of ⅞ inch diameter. The rivets in the battens and lattice were carbon steel of $\frac{7}{16}$ inch diameter. The rivets in all of the other columns were of soft steel ⅞ inch in diameter. The holes were drilled $\frac{9}{16}$ inch diameter in the case of the Metropolis Bridge and $\frac{11}{16}$ inch diameter in the case of the Memphis Bridge.

TABLE 2.—Properties of Steels

Name of column	Per cent of elements in chemical tests Averages								Tensile tests, pounds per square inch			
									Yield point			Break load, mean
	Ni	C	P	Mn	S	Si	Cr	Cu	Mean	High	Low	
Municipal Bridge:												
U_2 U_3	3.51	0.29	0.014	0.59	0.031	.....	.....	.....	55 500	63 100	50 500	93 300
U_8 U_9	3.59	.32	.015	.59	.033	.....	.....	.....	55 200	63 100	52 040	93 060
Metropolis Bridge:												
HC	.....	.36	.012	.43	.030	.....	.....	.....	40 700	50 000	37 590	76 660
HCl	.....	.36	.012	40	.030	.....	.....	.....	44 100	50 000	37 650	75 930
MY	1.12	.34	.010	.68	.037	0.10	0.53	0.10	59 900	68 380	55 890	100 610
MYl	1.12	.34	.010	.68	.037	.10	.53	.10	62 110	68 380	56 080	101 170
31HC	.....	.28	.017	.64	.031	.....	.....	.....	42 900	45 440	37 280	73 400
31HCl	.....	.28	.017	.64	.031	.....	.....	.....	42 700	45 440	37 280	74 400
32S	.....	.35	.017	.83	.039	.38	.....	.....	57 200	58 840	51 940	87 700
32Sl	.....	.35	.017	.83	.039	.38	.....	.....	56 500	57 480	51 940	88 300
34CS	.....	.31	.017	.49	.028	.13	.66	.....	55 800	59 290	48 260	82 700
34CSl	.....	.31	.017	.49	.028	.13	.66	.....	54 200	58 010	48 260	83 600
Memphis Bridge:												
US_2MS_1 carbon	.....	.23	.012	.49	.027	.....	.....	.....	41 740	43 700	40 250	65 420
US_2MS_1 Mayari	1.58	.33	.016	.64	.027	.....	.37	.....	62 430	72 160	52 000	99 800
U_2M_1 carbon	.....	.23	.012	.49	.029	.....	.....	.....	41 740	43 700	40 250	65 420
U_2M_1 Mayari	1.58	.33	.016	.64	.027	.....	.37	.....	62 830	72 160	52 000	99 800
LC_5LC_1 carbon	.....	.23	.012	.49	.029	.....	.....	.....	41 740	43 700	40 250	65 420
LC_5LC_1 Mayari	1.58	.33	.016	.64	.027	.....	.37	.....	62 430	72 160	52 000	99 800

TABLE 3.—Log of Test, Column U_2U_3, of Nickel Steel

[Cumulative Elongations (±) at Stations Below. Tested Jan. 16–17, 1913. Time of Test, Jan. 16, 9 a. m. to 4.27 p. m.; Jan. 17, 10.30 a. m. to 4.30 p. m.]

Load, pounds	Load in pounds per square inch	19	20	21	22	23	24	Average 19 to 24	25	26	27	28
177 600	2 000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000				
355 200	4 000	−.0013	−.0014	−.0009	−.0017	−.0018	−.0012	−.0014				
532 800	6 000	−.0029	−.0029	−.0029	−.0032	−.0033	−.0027	−.0030				
888 000	10 000	−.0054	−.0055	−.0051	−.0057	−.0055	−.0049	−.0054				
1 243 200	14 000	−.0081	−.0078	−.0077	−.0084	−.0079	−.0073	−.0079				
1 598 400	18 000	−.0110	−.0107	−.0106	−.0114	−.0109	−.0106	−.0109				
1 953 600	22 000	−.0144	−.0138	−.0136	−.0145	−.0141	−.0139	−.0141				
2 308 800	26 000	−.0172	−.0167	−.0166	−.0174	−.0168	−.0165	−.0169				
2 841 600	32 000	−.0216	−.0209	−.0206	−.0218	−.0212	−.0209	−.0212				
3 374 400	38 000	−.0265	−.0256	−.0252	−.0262	−.0259	−.0256	−.0258				
[a]3 729 600	42 000	−.0301	−.0289	−.0285	−.0297	−.0292	−.0285	−.0292	(b)	(b)	(b)	(b)
2 600 000	29 300	−.0205	−.0203	−.0200	−.0207	−.0203	−.0199	−.0203	(c)	(c)	(c)	(c)
3 729 600	42 000	−.0303	−.0293	−.0290	−.0300	−.0294	−.0293	−.0296	0.0000	0.0000	0.0000	0.0000
3 907 200	44 000	−.0322	−.0312	−.0309	−.0319	−.0312	−.0313	−.0315	−.0007	+.0003	−.0018	+.0003
4 084 800	46 000	−.0340	−.0330	−.0328	−.0337	−.0330	−.0330	−.0333	−.0027	+.0007	−.0045	+.0005
4 173 600	47 000	−.0354	−.0343	−.0343	−.0354	−.0345	−.0344	−.0347	−.0037	+.0008	−.0067	+.0008
4 262 400	48 000	−.0363	−.0355	−.0355	−.0367	−.0357	−.0353	−.0358	−.0045	+.0009	−.0095	+.0010
4 351 200	49 000	−.0386	−.0378	−.0379	−.0394	−.0382	−.0378	−.0383	−.0065	.....	−.0139	+.0019
4 440 000	50 000	−.0397	−.0391	−.0396	−.0413	−.0399	−.0392	−.0398	−.0074	+.0012	−.0166	+.0025
4 528 800	51 000	−.0406	−.0404	−.0410	−.0431	−.0416	−.0402	−.0412	−.0086	+.0013	−.0203	+.0035
4 617 600	52 000	−.0423	−.0424	−.0435	−.0458	−.0437	−.0420	−.0433	−.0098	+.0016	−.0235	+.0044
4 706 400	53 000	−.0442	−.0448	−.0463	−.0490	−.0468	−.0441	−.0459	−.0114	+.0018	−.0277	+.0057
4 795 200	54 000	−.0461	−.0472	−.0489	−.0525	−.0492	−.0461	−.0483	−.0127	+.0021	−.0311	+.0071
4 884 000	55 000	−.0484	−.0505	−.0529	−.0574	−.0530	−.0483	−.0518	−.0146	+.0020	−.0326	+.0085
4 972 800	56 000	−.0506	−.0537	−.0567	−.0615	−.0566	−.0507	−.0550	−.0158	+.0024	.....	+.0096
5 061 600	57 000	−.0544	−.0589	−.0627	−.0698	−.0629	−.0546	−.0606	−.0181	+.0027	.....	+.0115
5 150 400	58 000	−.0585	−.0666	−.0723	−.0823	−.0725	−.0601	−.0687	−.0210	+.0029	.....	+.0140
5 239 000	59 000	−.0644	−.0784	−.0876	−.1050	−.0878	−.0687	−.0820	.....	.....	.....	.....
[d]5 480 000	61 700	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....

[a] Test was stopped at 42 000 pounds per square inch Jan. 16, 4.30 p. m. This load was left on the column overnight, and had dropped to 29 300 pounds per square inch at 9.30 a. m. Jan. 17. This drop was due to a leak in the inlet pipe, which was repaired and test resumed. Test was started at 10.30 a. m. Jan. 17 and finished at 4.30 p. m. Jan. 17.

[b] Stopped Jan. 16.

[c] Started Jan. 17.

[d] Maximum load.

NOTE.—Stations 19 to 24 give ± elongations in gauge length of 20 inches. All other stations given ± elongations in gauge length of 8 inches.

See continuation of table for lattice-bar readings.

TABLE 3.—Log of Test, Column U_2U_3, of Nickel Steel—Continued

Load, pounds	Load in pounds per square inch	1	2	3	4	5	6	7	8	9	10
177 600	2 000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
355 200	4 000	+.0002	−.0002	−.0001	.0000	+.0001	+.0003	+.0004	+.0001	−.0002	−.0002
532 800	6 000	.0000	−.0002	.0000	+.0001	+.0001	+.0001	+.0003	+.0004	−.0004	−.0002
888 000	10 000	−.0001	−.0005	.0000	+.0001	+.0001	+.0002	+.0003	+.0001	−.0002	−.0004
1 243 200	14 000	−.0002	−.0008	−.0001	+.0002	+.0001	+.0002	+.0003	+.0003	−.0007	−.0006
1 598 400	18 000	−.0003	−.0010	−.0003	+.0003	+.0001	+.0002	+.0003	+.0003	−.0007	−.0007
1 953 600	22 000	−.0004	−.0011	−.0002	+.0004	+.0001	+.0002	+.0002	+.0002	−.0010	−.0009
2 308 800	26 000	−.0008	−.0015	−.0002	+.0003	+.0001	+.0001	+.0003	+.0003	−.0012	−.0011
2 841 600	32 000	−.0011	−.0018	−.0004	+.0003	+.0002	+.0001	+.0002	+.0004	−.0014	−.0011
3 374 400	38 000	−.0015	−.0022	−.0004	+.0003	+.0001	.0000	.0000	+.0008	−.0016	−.0014
3 729 600	42 000	−.0016	−.0027	−.0005	+.0003	+.0004	−.0001	.0000	+.0005	−.0021	−.0018
2 600 000	29 300	−.0010	−.0017	−.0003	+.0002	+.0003	+.0001	+.0002	+.0004	−.0011	−.0011
3 729 600	42 000	−.0019	−.0027	−.0006	+.0001	+.0001	−.0001	−.0001	.0000	−.0023	−.0021
3 907 200	44 000	−.0021	−.0030	−.0006	+.0002	+.0001	−.0003	−.0002	+.0001	−.0024	−.0035
4 084 800	46 000	−.0021	−.0031	−.0006	+.0002	+.0002	−.0001	−.0002	+.0001	−.0027	−.0021
4 173 600	47 000	−.0021	−.0033	−.0005	+.0002	+.0003	−.0003	−.0004	+.0005	−.0028	−.0022
4 262 400	48 000	−.0022	−.0034	−.0006	+.0002	+.0003	−.0002	−.0003	+.0006	−.0031	−.0022
4 351 200	49 000	−.0023	−.0035	−.0006	+.0002	.....	.....	.....	.....	−.0030	−.0023
4 440 000	50 000	−.0025	−.0036	−.0005	+.0004	−.0001	−.0003	−.0005	+.0001	−.0036	−.0025
4 528 800	51 000	−.0020	−.0036	−.0004	+.0004	+.0005	−.0002	−.0006	+.0004	−.0035	−.0027
4 617 600	52 000	−.0021	−.0036	−.0006	+.0004	+.0005	−.0004	−.0007	+.0004	−.0038	−.0028
4 706 400	53 000	−.0022	−.0040	−.0005	+.0002	−.0003	−.0002	−.0007	+.0004	−.00~0	−.0032
4 795 200	54 000	−.0026	−.0042	−.0006	+.0003	+.0007	−.0002	−.0007	+.0005	−.0042	−.0035
4 884 000	55 000	−.0026	−.0046	−.0006	+.0004	+.0009	−.0002	−.0007	.0000	−.0044	−.0038
4 972 800	56 000	−.0028	−.0046	−.0006	+.0002	.....	.....	.....	.....	−.0044	−.0039
5 061 600	57 000	−.0032	−.0046	−.0006	+.0002	+.0011	.0000	−.0010	+.0003	−.0048	−.0043
5 150 400	58 000	−.0035	−.0050	−.0004	+.0002	+.0011	.0000	−.0014	−.0004	−.0~50	−.0050
5 239 000	59 000	−.0043	−.0049	−.0021	+.0001	.....	.....	.....	.....	−.0052	.....

Load, pounds	Load in pounds per square inch	11	12	13	14	15	16	17	18
177 600	2 000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
355 200	4 000	.0000	.0000	+.0001	+.0002	+.0002	.0000	+.0003	+.0008
532 800	6 000	.0000	.0000	.0000	+.0004	+.0001	−.0002	+.0009	+.0016
888 000	10 000	.0000	.0000	−.0001	+.0002	.0000	−.0002	+.0016	+.0028
1 243 200	14 000	+.0001	+.0001	−.0001	+.0002	+.0002	−.0001	+.0026	+.0040
1 598 400	18 000	+.0001	+.0002	−.0001	+.0004	+.0002	−.0003	+.0035	+.0055
1 953 600	22 000	+.0001	+.0001	−.0001	+.0003	+.0002	−.0003	+.0043	+.0066
2 308 800	26 000	.0000	.0000	.0000	+.0004	+.0001	−.0002	+.0051	+.0079
2 841 600	32 000	+.0002	−.0001	.0000	+.0004	+.0002	−.0003	+.0067	+.0098
3 374 400	38 000	.0000	.0000	−.0001	+.0005	+.0001	−.0004	+.0083	+.0120
3 729 600	42 000	+.0002	−.0001	−.0003	+.0006	+.0002	−.0006	+.0093	+.0134
2 600 000	29 300	+.0001	.0000	.0000	+.0005	+.0002	−.0004	+.0073	+.0103
3 729 600	42 000	−.0001	−.0002	−.0005	+.0002	+.0001	−.0010	+.0098	+.0135
3 907 200	44 000	.0000	−.0001	−.0005	+.0004	+.0001	−.0019	+.0104	+.0143
4 084 800	46 000	+.0002	.0000	−.0005	+.0002	.0000	−.0008	+.0113	+.0150
4 173 600	47 000	+.0003	.0000	−.0005	+.0002	+.0001	−.0008	+.0118	+.0156
4 262 400	48 000	+.0004	+.0001	−.0005	+.0004	+.0002	−.0008	+.0124	+.0160
4 351 200	49 000	+.0004	+.0002	−.0005	+.0002	.....	.....	+.0133	+.0170
4 440 000	50 000	+.0006	+.0003	−.0005	+.0001	.0000	−.0007	+.0139	+.0176
4 528 800	51 000	+.0008	+.0005	−.0005	.0000	.0000	−.0009	+.0145	+.0186
4 617 600	52 000	+.0008	+.0005	−.0005	.0000	.0000	−.0007	+.0151	+.0194
4 706 400	53 000	+.0007	+.0005	−.0005	.0000	.0000	−.0008	+.0161	+.0203
4 795 200	54 000	+.0007	+.0006	−.0004	.0000	.0000	−.0007	+.0168	+.0212
4 884 000	55 000	+.0008	+.0008	−.0005	.0000	−.0001	−.0008	+.0177	+.0221
4 972 800	56 000	+.0007	+.0008	.....	.....	.....	.....	+.0206	+.0226
5 061 600	57 000	+.0008	+.0010	−.0011	.0000	−.0001	−.0008	+.0203	+.0230
5 150 400	58 000	+.0004	+.0010	−.0005	+.0001	.....	−.0008	+.0227	+.0233
5 239 000	59 000	.....	.....	.....	.....	.....	.....	.....	.....

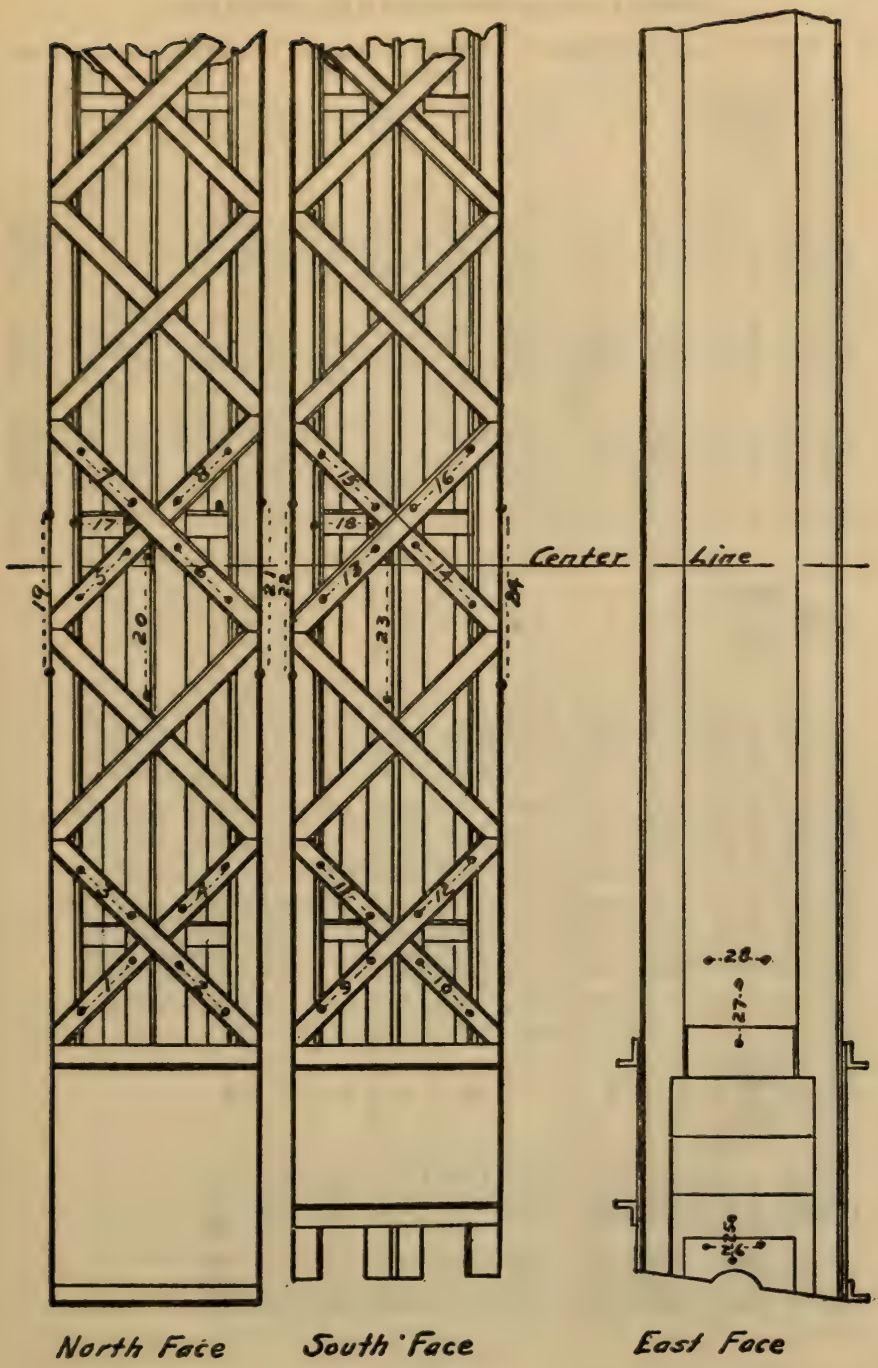


FIG. 3.—*Column U_2U_3 (nickel steel). Key to stations on Table 3*

TABLE 4.—Log of Test Column U_8U_9 of Nickel Steel

[Cumulative (±) Elongations at Stations Below. Tested Jan. 28, 1913. Time of Test, 9.30 a. m. to 4 p. m.]

Load, pounds	Load in pounds per square inch	47	48	49	50	51	52	Average, 47 to 52	53	54	55	56
110 300	1 000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	Total compression not measured. Values below are total compression reckoned from "e."	0.0000
551 500	5 000	−.0030	−.0025	−.0028	−.0025	−.0026	−.0024	−.0026	−.0014	+.0004		+.0006
1 103 000	10 000	−.0062	−.0063	−.0061	−.0053	−.0057	−.0056	−.0059	−.0028	+.0008		+.0008
1 654 500	15 000	−.0094	−.0091	−.0091	−.0087	−.0090	−.0089	−.0090	−.0043	+.0013		+.0015
2 206 000	20 000	−.0128	−.0132	−.0123	−.0118	−.0125	−.0123	−.0125	−.0058	+.0017		+.0016
2 757 500	25 000	−.0160	−.0166	−.0154	−.0151	−.0160	−.0157	−.0158	−.0074	+.0022		+.0022
3 309 000	30 000	−.0196	−.0199	−.0188	−.0185	−.0195	−.0191	−.0192	−.0089	+.0025		+.0028
3 860 500	35 000	−.0232	−.0239	−.0225	−.0222	−.0236	−.0231	−.0231	−.0105	+.0029		+.0031
4 412 000	40 000	−.0280	−.0287	−.0272	−.0271	−.0287	−.0281	−.0280	−.0124	+.0035		+.0035
4 963 500	45 000	−.0316	−.0330	−.0308	−.0314	−.0333	−.0325	−.0321	−.0144	+.0041	e+o	+.0042
5 239 250	47 500	−.0338	−.0355	−.0329	−.0336	−.0362	−.0350	−.0345	−.0157	+.0045	0.0011	+.0046
5 515 000	50 000	−.0363	−.0384	−.0352	−.0364	−.0396	−.0378	−.0373	−.0171	+.0051	−.0028	+.0052
5 735 600	52 000	−.0384	−.0411	−.0373	−.0386	−.0431	−.0403	−.0398	−.0185	+.0055	−.0044	+.0062
5 956 200	54 000	−.0409	−.0446	−.0397	−.0416	−.0474	−.0432	−.0429	−.0202	+.0064	−.0064	+.0068
6 176 800	56 000	−.0441	−.0493	−.0431	−.0452	−.0536	−.0472	−.0471	−.0232	+.0077	−.0096	+.0080
6 397 400	58 000	−.0478	−.0557	−.0477	−.0504	−.0642	−.0535	−.0532	−.0271	+.0091	−.0142	+.0102
[a]6 768 500	61 400	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....

Load, pounds	Load in pounds per square inch	37	38	39	40	41	42	43	44	45	46
110 300	1 000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
551 500	5 000	−.0010	−.0010	−.0012	−.0011	+.0014	+.0020	−.0010	−.0011	−.0012	−.0013
1 103 000	10 000	−.0025	−.0027	−.0026	−.0025	+.0027	+.0035	−.0026	−.0025	−.0026	−.0039
1 654 500	15 000	−.0041	−.0042	−.0040	−.0039	+.0042	+.0054	−.0040	−.0038	−.0041	−.0045
2 206 000	20 000	−.0056	−.0055	−.0055	−.0049	+.0058	+.0073	−.0054	−.0051	−.0056	−.0061
2 757 500	25 000	−.0071	−.0073	−.0069	−.0067	+.0073	+.0091	−.0069	−.0066	−.0071	−.0078
3 309 000	30 000	−.0088	−.0092	.....	−.0081	+.0089	+.0111	−.0083	−.0080	−.0087	−.0093
3 860 500	35 000	−.0106	−.0117	.....	−.0098	+.0104	+.0131	−.0097	−.0094	−.0104	−.0111
4 412 000	40 000	−.0127	−.0137	.....	−.0117	+.0121	+.0144	−.0112	−.0110	−.0122	−.0129
4 963 500	45 000	−.0151	−.0164	.....	−.0138	+.0137	+.0160	−.0128	−.0126	−.0145	−.0148
5 239 250	47 500	−.0165	−.0178	.....	−.0150	+.0147	+.0173	−.0137	−.0136	−.0156	−.0159
5 515 000	50 000	−.0178	−.0195	.....	−.0164	+.0159	.....	−.0146	−.0145	−.0172	−.0170
5 735 600	52 000	−.0191	−.0210	.....	−.0175	+.0195	.....	−.0153	−.0152	−.0185	−.0184
5 956 200	54 000	−.0206	−.0234	.....	−.0193	+.0197	.....	−.0166	−.0165	−.0204	−.0202
6 176 800	56 000	−.0234	−.0264	.....	−.0215	+.0197	.....	−.0182	−.0177	−.0230	−.0231
6 397 400	58 000	.....	−.0321	.....	−.0246	+.0197	.....	−.0206	−.0191	−.0271	.....

Load, pounds	Load in pounds per square inch	29	30	31	32	33	34	35	36
110 500	1 000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
551 500	5 000	−.0002	.0000	.0000	−.0001	−.0001	.0000	−.0001	.0000
1 103 000	10 000	−.0004	−.0001	−.0002	−.0003	.0000	−.0002	.0000	−.0001
2 206 000	20 000	−.0006	−.0003	−.0006	−.0006	−.0001	−.0002	−.0001	−.0003
3 309 000	30 000	−.0010	−.0009	−.0005	−.0007	+.0003	−.0003	−.0001	−.0004
4 412 000	40 000	−.0014	−.0012	−.0006	−.0009	+.0001	.0000	.0000	−.0005
5 515 000	50 000	−.0021	−.0017	−.0005	−.0012	−.0002	−.0002	+.0005	−.0006
6 397 400	58 000	−.0026	−.0016	.0000	−.0011	−.0005	−.0002	−.0002	−.0006

[a] Maximum load.

NOTE.—Stations 47 to 52, inclusive, give ± elongations for gauge length of 20 inches. All other stations give ± elongations for gauge length of 8 inches.

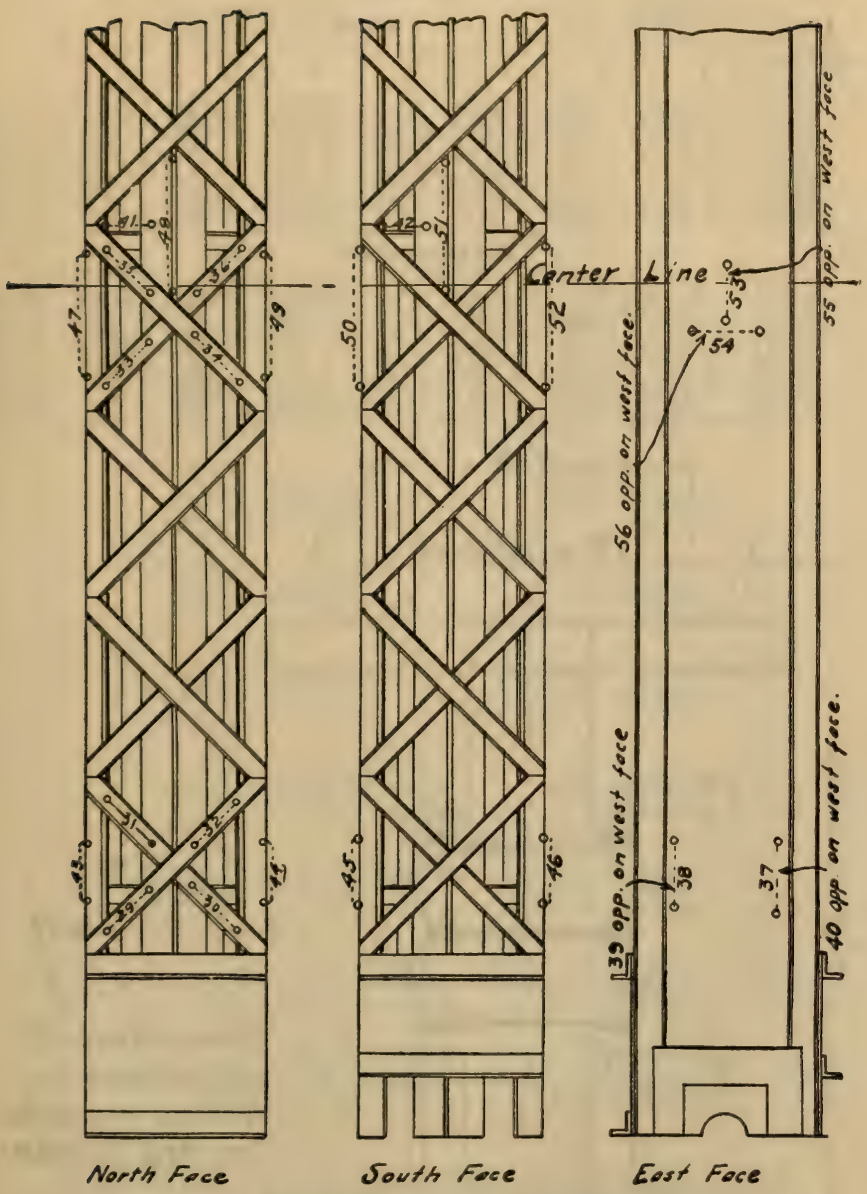


FIG. 4.—*Column U_3U_3 (nickel steel). Key to stations on Table 4*

TABLE 5.—Cumulative Components of Deflection at Mid-Length in Inches

[+ sign denotes displacement from unstrained axis: − sign denotes displacement toward unstrained axis.]

FOR COLUMN U_2U_8

Loads, pounds per square inch	Stations							
	a	b	c	d	e	f	g	h
10 000	+0.040	−0.007	+0.018	+0.018	+0.026	−0.015	+0.045	−0.002
22 000	+ .065	− .014	+ .030	+ .015	+ .033	− .021	+ .074	+ .001
32 000	+ .057	− .011	+ .041	+ .012	+ .042	− .019	+ .103	+ .002
47 000	+ .114	− .013	+ .050	+ .026	+ .052	− .020	+ .159	− .004
50 000	+ .136	− .010	+ .046	+ .030	+ .052	− .015	+ .170	− .009
55 000	+ .183	+ .002	+ .022	+ .046	+ .033	− .025	+ .234	− .017
59 000	+ .346	+ .048	− .091	+ .097	− .087	− .032	+ .416	− .054

FOR COLUMN U_8U_9

1000	0	0	0	0	0	0	0	0
10 000	−0.005	0	+0.026	−0.007	+0.038	+0.017	+0.022	+0.005
20 000	+ .004	+0.002	+ .048	− .004	+ .061	+ .016	+ .042	+ .005
30 000	+ .015	+ .005	+ .065	+ .006	+ .083	+ .011	+ .059	+ .001
40 000	+ .027	+ .075	+ .081	+ .014	+ .105	− .003	+ .077	− .007
50 000	+ .045	+ .028	+ .093	+ .051	+ .119	− .030	+ .085	+ .025
54 000	+ .055	+ .049	+ .094	+ .073	+ .118	− .065	+ .109	− .047
58 000	+ .100	+ .128	+ .068	+ .166	+ .113	− .160	+ .159	+ .121

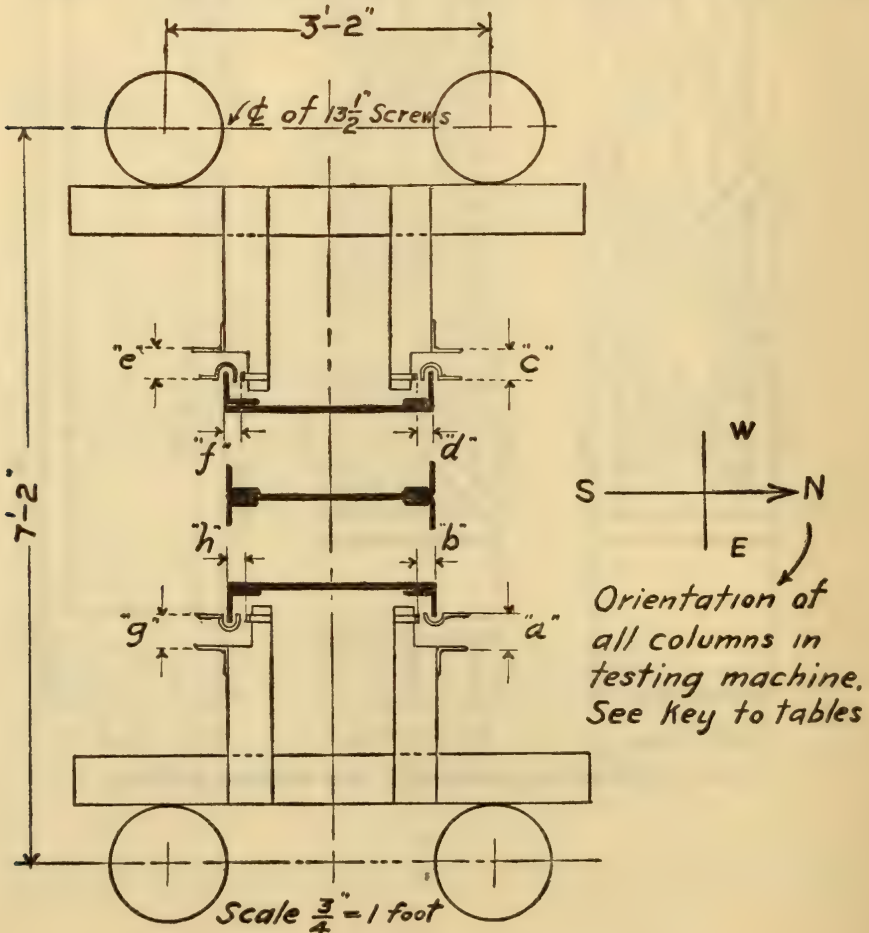


FIG. 5.—*Key to deflection stations above*

TABLE 6.—Log of Test, Column HC, of High-Carbon Steel

[Area=76.14. Cumulative Elongations (±) at Stations Below, Tested Jan. 12, 1914. Time of Test, 9 a. m. to 3.30 p. m.]

Load, pounds	Load in pounds per square inch	1	2	3	4	5	6	7	8	9	10	11	12	13
76 140	1000	0	0	0	0	0	0	0	0	0	0	0	0	0
152 280	2000	−0.0054	−0.0004	+0.0001	+0.0009	−0.0002	−0.0044	−0.0007	+0.0004	+0.0002	−0.0006	−0.0007	−0.0004	−0.0005
228 420	3000	− .0096	− .0006	+ .0001	+ .0012	− .0004	− .0089	− .0011	+ .0022	+ .0003	− .0009	− .0010	− .0008	− .0009
320 000	4200	− .0151	− .0011	− .0012	+ .0006	− .0009	− .0143	− .0016	+ .0018	0	− .0013	− .0011	− .0014	− .0015
380 700	5000	− .0176	− .0012	− .0021	+ .0002	− .0012	− .0165	− .0020	+ .0017	+ .0002	− .0016	− .0016	− .0018	− .0019
761 400	10 000	− .0319	− .0027	− .0139	− .0102	− .0027	− .0351	− .0038	+ .0003	− .0010	− .0033	− .0031	− .0051	− .0049
1 142 100	15 000	− .0529	− .0045	− .0272	− .0236	− .0042	− .0529	− .0054	− .0011	− .0025	− .0049	− .0044	− .0091	− .0090
1 522 800	20 000	− .0702	− .0057	− .0410	− .0389	− .0058	− .0699	− .0074	− .0023	− .0040	− .0064	− 0056	− 0125	− 0127
1 903 500	25 000	− 0909	− 0075	− 0582	− 0570	− .0076	− .0897	− .0094	− .0046	− .0058	− .0082	− .0078	− .0177	− .0180
2 284 200	30 000	− .1162	− .0097	− .0802	− .0791	− .0098	− .1154	− .0124	− .0069	− .0082	− .0102	− .0101	− .0236	− .0250
2 664 900	35 000	− .2474	− .0249	− .1769	− .1631	− .0245	− .2319	− .0139	− .0162	− .0172	− .0198	− .0122	.....	.....
[a] 2 683 500	35 300	.....	.....	.....	.....	.....	.....	.....	(c)	.....	.....	.....	.....	.....
[b] 2 920 000	38 400	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....

Load, pounds	Load in pounds per square inch	14	15	16	17	18	19	20	21	22	23	24	25
76 140	1000	0	0	0	0	0	0	0	0	0	0	0	0
152 280	2000	−0.0008	−0.0032	+0.0001	0	−0.0003	−0.0002	−0.0003	0	+0.0078	−0.0003	−0.0004	−0.0003
228 420	3000	− .0007	− .0034	+ .0002	−0.0002	− .0003	− .0004	− .0009	−0.0007	+ .0062	− .0009	− .0010	− .0007
320 000	4200	− .0010	− .0033	− .0005	− .0003	− .0005	− .0012	− .0007	− .0007	+ .0072	− .0013	− .0011	− .0005
380 700	5000	− .0013	− .0037	− .0001	− .0002	− .0006	− .0009	− .0006	− .0008	+ .0074	− .0014	− .0008	− .0013
761 400	10 000	− .0029	− .0051	− .0005	− .0005	− .0021	− .0019	− .0012	− .0014	+ .0065	− .0030	− .0029	− .0028
1 142 100	15 000	− .0046	− .0068	− .0005	− .0009	− .0036	− .0035	− .0020	− .0021	+ .0042	− .0048	− .0045	− .0043
1 522 800	20 000	− .0066	− .0085	− .0007	− .0009	− .0057	− .0051	− .0026	− .0025	+ .0026	− .0069	− .0067	− .0071
1 903 500	25 000	− .0089	− .0100	− .0008	− .0010	− .0079	− .0066	− .0033	− .0034	+ .0002	− .0092	− .0087	− .0085
2 284 200	30 000	− .0145	− .0120	− .0009	− .0011	− .0113	− .0086	− .0038	− .0042	− .0038	− .0113	− .0111	− .0109
2 664 900	35 000	− .0334	− .0160	− .0013	− .0021	− .0283	.....	.....	.....	(c)	− .0127	− .0136	− .0138

[a] Maximum load. Buckled to north 2 inches at center. Lattice buckled at center.
[b] Maximum load after buckling=secondary failure.
[c] The initial reading was probably in error in taking measurements.

TABLE 6.—Log of Test, Column HC, of High-Carbon Steel—Continued

Load, pounds	Load in pounds per square inch	26	27	28	29	30	31	32	33	34	35	36	37
76 140	1000	0	0	0	0	0	0	0	0	0	0	0	0
152 280	2000	−0.0002	−0.0010	−0.0002	−0.0001	0	0	−0.0003	−0.0001	−0.0003	0	−0.0002	−0.0008
228 420	3000	− .0010	+ .0002	− .0002	− .0002	−0.0001	−0.0030	+ .0001	+ .0002	− .0002	0	0	0
320 000	4200	− .0005	0	− .0002	− .0002	0	− .0031	+ .0001	− .0001	− .0005	−0.0002	− .0001	− .0011
380 700	5000	− .0007	0	0	− .0002	− .0006	− .0034	− .0001	− .0003	− .0007	+ .0002	− .0002	− .0008
761 400	10 000	− .0024	− .0002	− .0006	− .0007	− .0003	− .0042	− .0013	− .0020	− .0012	+ .0002	− .0004	− .0012
1 142 100	15 000	− .0045	− .0005	− .0006	− .0010	− .0010	− .0047	− .0027	− .0029	− .0019	+ .0001	− .0005	− .0019
1 522 800	20 000	− .0057	− .0006	− .0009	− .0012	− .0011	− .0053	− .0037	− .0041	− .0024	0	− .0009	− .0020
1 903 500	25 000	− .0075	− .0007	− .0011	− .0014	− .0012	− .0063	− .0044	− .0052	− .0032	0	− .0011	− .0024
2 284 200	30 000	− .0103	− .0007	− .0013	− .0016	− .0013	− .0068	− .0052	− .0057	− .0044	0	− .0011	− .0027
2 664 900	35 000	− .0144	.....	.....	.....	.....	− .0080	− .0063	− .0085	− .0053	+ .0003	− .0013	− .0028

Load, pounds	Load in pounds per square inch	38	39	40	41	42	43	44	45	46	47	48	49
76 140	1000	0	0	0	0	0	0	0	0	0	0	0	0
152 280	2000	−0.0002	−0.0002	−0.0001	−0.0003	−0.0004	+0.0002	+0.0005	−0.0002	0	−0.0001	−0.0006	−0.0003
228 420	3000	− .0003	0	− .0001	− .0002	0	+ .0001	+ .0003	− .0001	+0.0001	+ .0002	− .0010	− .0005
320 000	4200	− .0004	− .0002	− .0001	− .0002	+ .0001	− .0001	+ .0023	+ .0010	+ .0003	+ .0005	− .0015	− .0007
380 700	5000	− .0004	− .0003	− .0001	− .0002	+ .0002	+ .0004	+ .0023	+ .0011	+ .0010	+ .0006	− .0016	− .0009
761 400	10 000	− .0011	− .0009	− .0004	− .0003	− .0008	+ .0004	+ .0023	+ .0011	+ .0006	+ .0008	− .0033	− .0015
1 142 100	15 000	− .0015	− .0013	− .0007	− .0003	0	+ .0005	+ .0023	+ .0011	+ .0004	+ .0014	− .0050	− .0033
1 522 800	20 000	− .0019	− .0016	− .0010	− .0004	+ .0006	+ .0006	+ .0027	+ .0015	+ .0008	.....	− .0066	− .0061
1 903 500	25 000	− .0023	− .0021	− .0012	− .0007	+ .0006	+ .0009	+ .0023	+ .0013	+ .0011	.....	− .0080	− .0073
2 284 200	30 000	− .0026	− .0024	− .0015	− .0009	+ .0005	+ .0007	+ .0023	+ .0011	+ .0009	.....	− .0099	− .0123
2 664 900	35 000	− .0028	− .0026	− .0018	− .0009	+ .0005	+ .0007	+ .0037	+ .0016	.....	.....	− .0156	− .0359

NOTE.—Stations 1, 3, 4, and 6 give compressions in inches in gauge length of 80 inches. Other stations give (±) elongations in inches in gauge length of 8 inches.

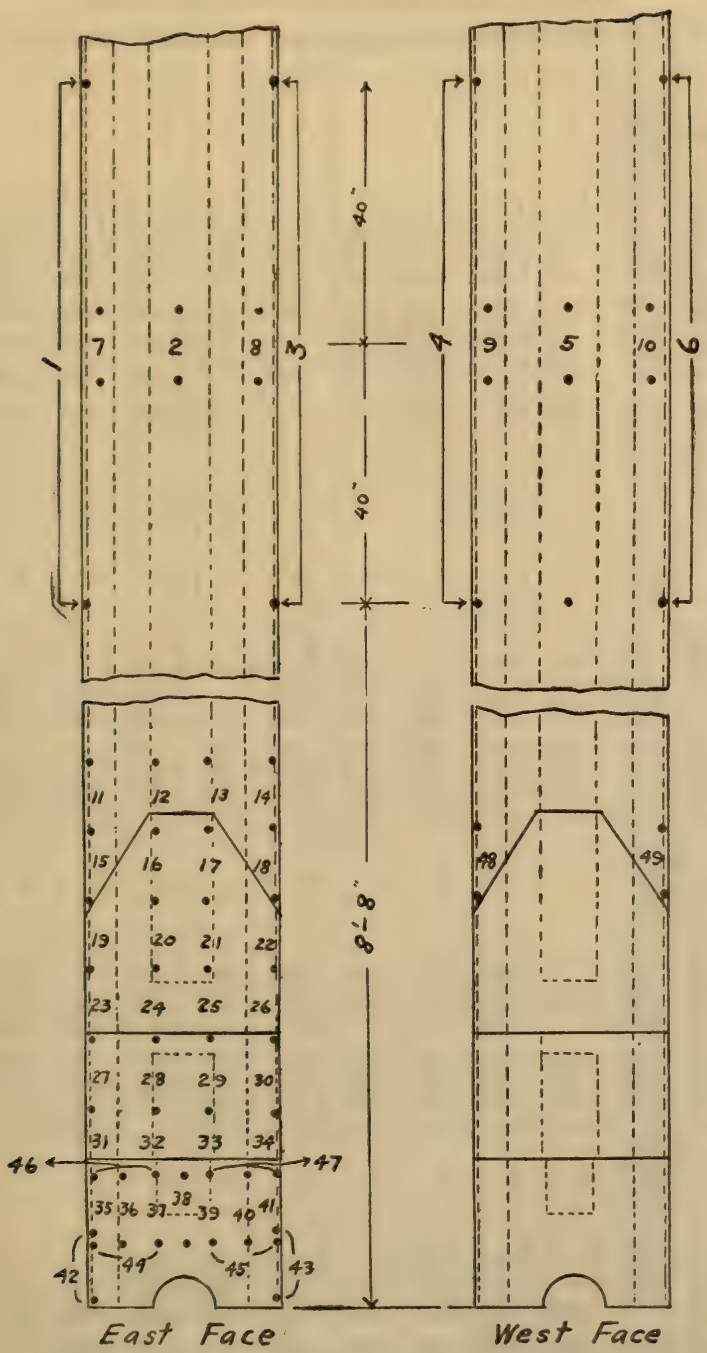


FIG. 6.—*Column HC (carbon steel). Key to stations on Table 6*

TABLE 7.—Log of Test, Column MY, of Mayari Steel

[Area=76.14. Cumulative (±) Elongations at Stations Below. Tested Jan. 13, 1914. Time of Test, 1.30 to 4.45 p. m.]

Load, pounds	Load in pounds per square inch	1	2	3	4	5	6	7	8	9	10
76 140	1000	0	0	0	0	0	0	0	0	0	0
152 280	2000	−.0044	−.0002	−.0039	−.0011	−.0004	−.0071	−.0006	0	−.0001	−.0007
380 700	5000	−.0150	−.0010	−.0050	−.0073	−.0013	−.0170	−.0016	−.0006	−.0003	−.0017
761 400	10 000	−.0297	−.0024	−.0178	−.0201	−.0027	−.0380	−.0031	−.0020	−.0017	−.0032
1 142 100	15 000	−.0437	−.0040	−.0306	−.0339	−.0041	−.0460	−.0047	−.0034	−.0031	−.0047
1 522 800	20 000	−.0572	−.0054	−.0437	−.0474	−.0054	−.0598	−.0061	−.0046	−.0045	−.0062
1 903 500	25 000	−.0718	.....	−.0569	−.0613	.....	−.0740	.....	.....	.....	.....
2 284 200	30 000	−.0874	−.0083	−.0715	−.0760	−.0080	−.0884	−.0092	−.0076	−.0072	−.0090
2 664 900	35 000	−.1039	.....	−.0868	−.0903	.....	−.1037	.....	.....	.....	.....
3 045 600	40 000	−.1233	−.0118	−.1042	−.1061	−.0113	−.1193	−.0126	−.0112	−.0104	−.0120
3 426 300	45 000	−.1479	−.0142	−.1245	−.1245	−.0131	−.1387	−.0150	−.0133	−.0121	−.0140
3 578 600	47 000	−.1595	.....	−.1364	−.1335	.....	−.1485	.....	.....	.....	.....
[a] 3 740 000	49 200	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
[b] 4 360 000	57 300	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
[c] 4 500 000	59 200	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
[d] 4 682 500	61 500	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....

Load, pounds	Load in pounds per square inch	15	18	46	47	48	49	50	51	52	53
76 140	1000	0	0	0	0	0	0	0	0	0	0
152 280	2000	−.0002	+.0006	−.0002	−.0008	+.0005	+.0002	−.0003	0	−.0003	0
380 700	5000	−.0015	0	−.0010	−.0017	+.0002	0	−.0001	−.0002	−.0005	−.0001
761 400	10 000	−.0030	−.0014	−.0022	−.0034	+.0004	0	−.0008	−.0006	−.0016	−.0004
1 142 100	15 000	−.0044	−.0028	−.0036	−.0048	+.0004	−.0004	−.0010	−.0008	−.0020	−.0010
1 522 800	20 000	−.0062	−.0042	−.0049	−.0062	−.0004	−.0007	−.0007	−.0010	−.0018	−.0013
2 284 200	30 000	−.0092	−.0073	−.0076	−.0090	−.0010	−.0014	−.0012	−.0013	−.0021	−.0018
3 045 600	40 000	−.0128	−.0116	−.0104	−.0116	−.0017	−.0022	−.0015	−.0020	−.0022	−.0026
3 426 300	45 000	−.0156	−.0148	−.0122	−.0134	−.0022	−.0026	−.0014	−.0024	−.0032	−.0032

Load, pounds	Load in pounds per square inch	54	55	56	57	58	59	60	61	62	63
76 140	1000	0	0	0	0	0	0	0	0	0	0
152 280	2000	0	+.0004	+.0007	−.0002	+.0003	+.0001	+.0003	0	−.0007	−.0023
380 700	5000	+.0002	+.0001	+.0008	−.0004	+.0001	+.0006	+.0015	−.0006	−.0004	−.0019
761 400	10 000	+.0004	−.0003	+.0012	−.0002	−.0012	+.0010	+.0013	−.0008	−.0020	−.0022
1 142 100	15 000	0	−.0007	+.0014	0	+.0003	+.0015	+.0017	−.0006	−.0008	−.0025
1 522 800	20 000	−.0006	−.0010	+.0015	−.0006	+.0007	+.0012	+.0017	−.0004	−.0007	−.0037
2 284 200	30 000	−.0014	−.0016	+.0027	+.0002	+.0007	+.0019	+.0021	−.0002	−.0014	−.0033
3 045 600	40 000	−.0020	−.0024	+.0027	+.0016	+.0005	+.0023	+.0026	+.0002	−.0018	−.0033
3 426 300	45 000	−.0024	−.0028	+.0028	+.0020	+.0011	+.0031	+.0029	+.0004	−.0022	−.0037

Load, pounds	Load in pounds per square inch	64	65	66	67	68	69	70	71
76 140	1000	0	0	0	0	0	0	0	0
152 280	2000	0	−.0001	+.0024	0	−.0001	−.0006	+.0002	0
380 700	5000	+.0001	−.0003	+.0024	0	−.0002	−.0006	+.0003	+.0006
761 400	10 000	0	−.0027	+.0016	−.0001	−.0012	−.0006	+.0011	+.0011
1 142 100	15 000	−.0001	−.0031	+.0017	−.0005	−.0008	−.0012	+.0011	+.0016
1 522 800	20 000	−.0002	−.0029	+.0014	−.0007	−.0012	−.0014	+.0015	+.0022
2 284 200	30 000	−.0005	−.0037	+.0011	−.0014	−.0014	−.0008	+.0035	+.0032
3 045 600	40 000	−.0006	−.0035	+.0007	−.0022	−.0018	−.0001	+.0039	+.0042
3 426 300	45 000	−.0010	−.0041	+.0002	−.0028	−.0018	.0000	+.0055	+.0045

[a] Scaling of steel.
[b] Buckling north about 1 inch.
[c] Buckling north about 1½ inches.
[d] Buckling north about 2½ inches. Maximum load. Load fell off.

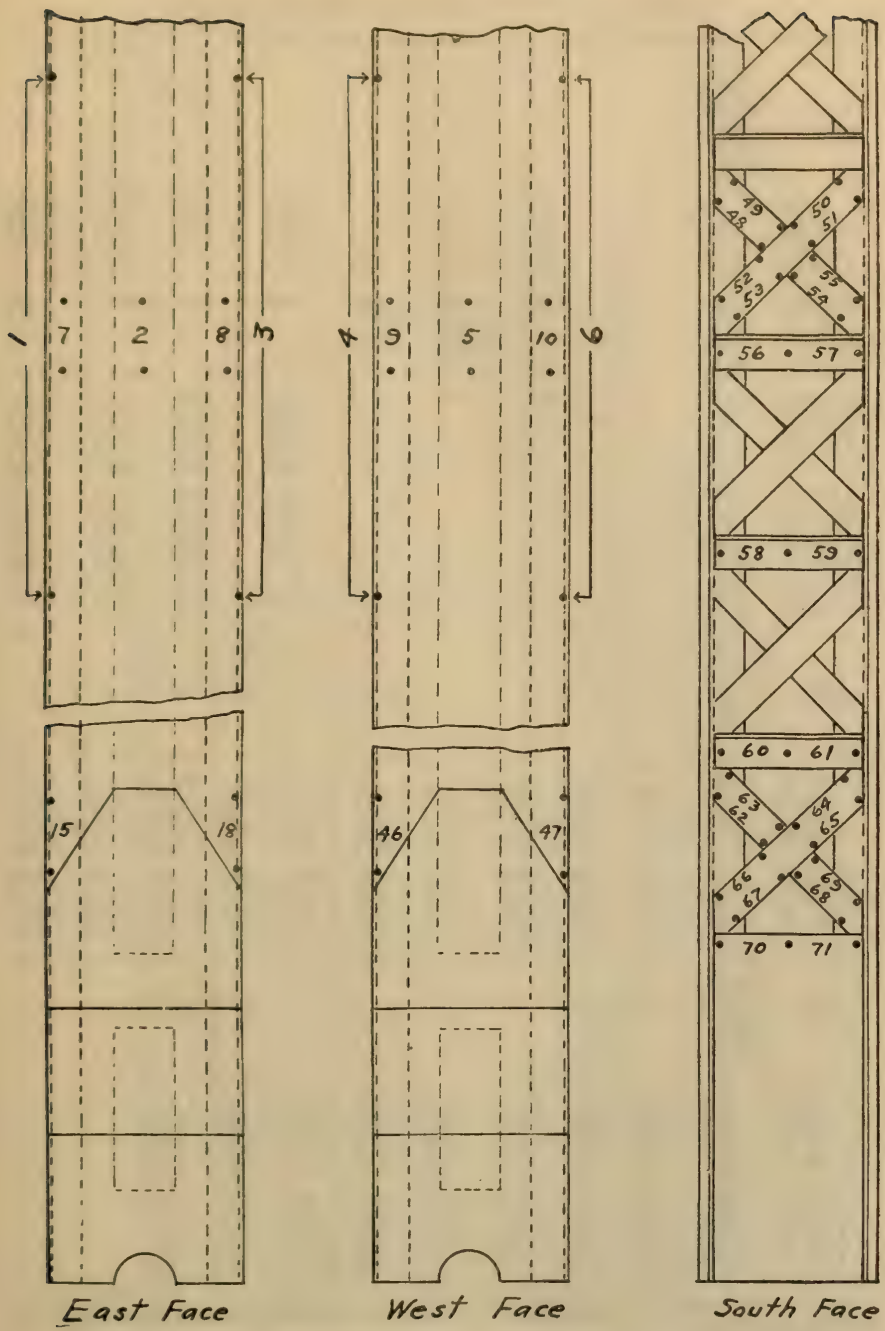


FIG. 7.—*Column MY (Mayari steel). Key to stations on Table 7*

TABLE 8.—Log of Test, Column 31HC, Carbon Steel

[Cumulative (±) Elongations at Stations Below. Tested July 7, 1914. Time of Test, 9.35 a. m. to 12.17 p. m.]

Load, pounds	Load in pounds per square inch	First run [a] 1	2	3	4	Second run 1	2	3	4
75 990	1000	0	0	0	0	−0.0070	−0.0028	−0.0019	−0.0061
379 950	5000	−.0145	−.0072	−.0071	−.0144	−.0203	−.0106	−.0090	−.0195
759 900	10 000	−.0291	−.0200	−.0200	−.0293	−.0345	−.0230	−.0219	−.0335
987 870	13 000	−.0390	−.0280	−.0276	−.0385	.....	.....	.....	.....
1 063 860	14 000	−.0417	−.0309	−.0304	−.0414	.....	.....	.....	.....
1 139 850	15 000	−.0440	−.0332	−.0330	−.0440	−.0481	−.0364	−.0350	−.0470
1 215 840	16 000	−.0477	−.0368	−.0360	−.0474	.....	.....	.....	.....
1 291 830	17 000	−.0508	−.0393	−.0386	−.0505	.....	.....	.....	.....
1 367 820	18 000	−.0542	−.0420	−.0410	−.0535	.....	.....	.....	.....
1 443 810	19 000	−.0573	−.0453	−.0439	−.0566	.....	.....	.....	.....
1 519 800	20 000	−.0608	−.0483	−.0470	−.0599	−.0618	−.0495	−.0475	−.0607
1 671 780	22 000	.....	.....	.....	.....	−.0688	−.0552	−.0536	−.0675
1 823 760	24 000	.....	.....	.....	.....	−.0760	−.0625	−.0598	−.0750
1 899 750	25 000	.....	.....	.....	.....	−.0807	−.0662	−.0631	−.0783
1 975 740	26 000	.....	.....	.....	.....	−.0852	−.0703	−.0670	−.0832
2 127 720	28 000	.....	.....	.....	.....	−.0951	−.0792	−.0749	−.0923
2 279 700	30 000	.....	.....	.....	.....	−.1063	−.0884	−.0840	−.1025
[b] 2 431 680	32 000	.....	.....	.....	.....	−.1210	−.1009	−.0942	−.1156
[c] 2 583 660	34 000	.....	.....	.....	.....	−.1400	−.1166	−.1083	−.1334
[d] 2 659 650	35 000	.....	.....	.....	.....	−.1545	−.1267	−.1180	−.1457
[e, f] 2 887 620	38 000	.....	.....	.....	.....	−.1902	−.1516	−.1418	−.1813
[g] 3 172 000	41 740	.....	.....	.....	.....	.....	.....	.....	.....

Load, pounds	Load in pounds per square inch	5	6	7	8	9	10	11	12	13	14
75 990	1000	0	0	0	0	0	0	0	0	0	0
[h] 75 990	1000	.0000	.0000	.0000	.0000	+.0001	−.0001	.0000	−.0001	.0000	+.0001
379 950	5000	−.0015	−.0012	−.0009	−.0008	−.0010	−.0016	+.0004	+.0003	+.0002	+.0005
759 900	10 000	−.0031	−.0026	−.0021	−.0022	−.0025	−.0031	+.0008	+.0008	+.0008	+.0009
1 139 850	15 000	−.0046	−.0042	−.0037	−.0035	−.0038	−.0048	+.0014	+.0012	+.0011	+.0013
1 519 800	20 000	−.0063	−.0057	−.0052	−.0051	−.0054	−.0064	+.0019	+.0018	+.0014	+.0019
1 899 750	25 000	−.0083	−.0078	−.0068	−.0068	−.0071	−.0082	+.0027	+.0025	+.0021	+.0024
2 279 700	30 000	−.0110	−.0107	−.0090	−.0093	−.0093	−.0108	+.0039	+.0035	+.0029	+.0034
2 659 650	35 000	−.0157	−.0156	−.0125	−.0133	−.0133	−.0161	+.0064	+.0058	+.0045	+.0057

Load, pounds	Load in pounds per square inch	15	16	17	18	19	20	21	22
75 990	1000	0	0	0	0	0	0	0	0
[h] 75 990	1000	+.0002	−.0004	+.0001	−.0003	−.0003	.0000	+.0001	+.0001
379 950	5000	−.0004	−.0014	−.0019	−.0014	−.0016	−.0013	−.0018	−.0009
759 900	10 000	−.0026	−.0037	−.0046	−.0033	−.0034	−.0032	−.0038	−.0028
1 139 850	15 000	−.0044	−.0056	−.0074	−.0050	−.0055	−.0049	−.0067	−.0046
1 519 800	20 000	−.0075	−.0078	−.0104	−.0065	−.0085	−.0076	−.0093	−.0058
75 990	1000	−.0001	−.0011	+.0004	−.0010	−.0009	−.0001	+.0001	+.0010
1 899 750	25 000	−.0100	−.0100	−.0134	−.0080	−.0109	−.0096	−.0120	−.0073
2 279 700	30 000	−.0129	−.0124	−.0166	−.0094	−.0141	−.0118	−.0153	−.0085
2 659 650	35 000	−.0162	−.0148	−.0200	−.0111	−.0195	−.0165	−.0207	−.0099

[a] First run taken from 1000 to 20 000, then back to 1000, and readings continued to maximum load on second run as shown.
[b] Scaling of steel.
[c] Loud "creaking."
[d] Load dropped to 2 600 000.
[e] Scaling freely at 2 730 000.
[f] This load was probably 2 787 620.
[g] Maximum load.
[h] Repetition for check readings.

NOTE.—Stations 1 to 4 give compression in inches in gauge length of 80 inches. Stations 5 to 14, inclusive, give (±) elongations in inches in gauge length of 8 inches, while stations 15 to 22, inclusive, are for 16 inches.

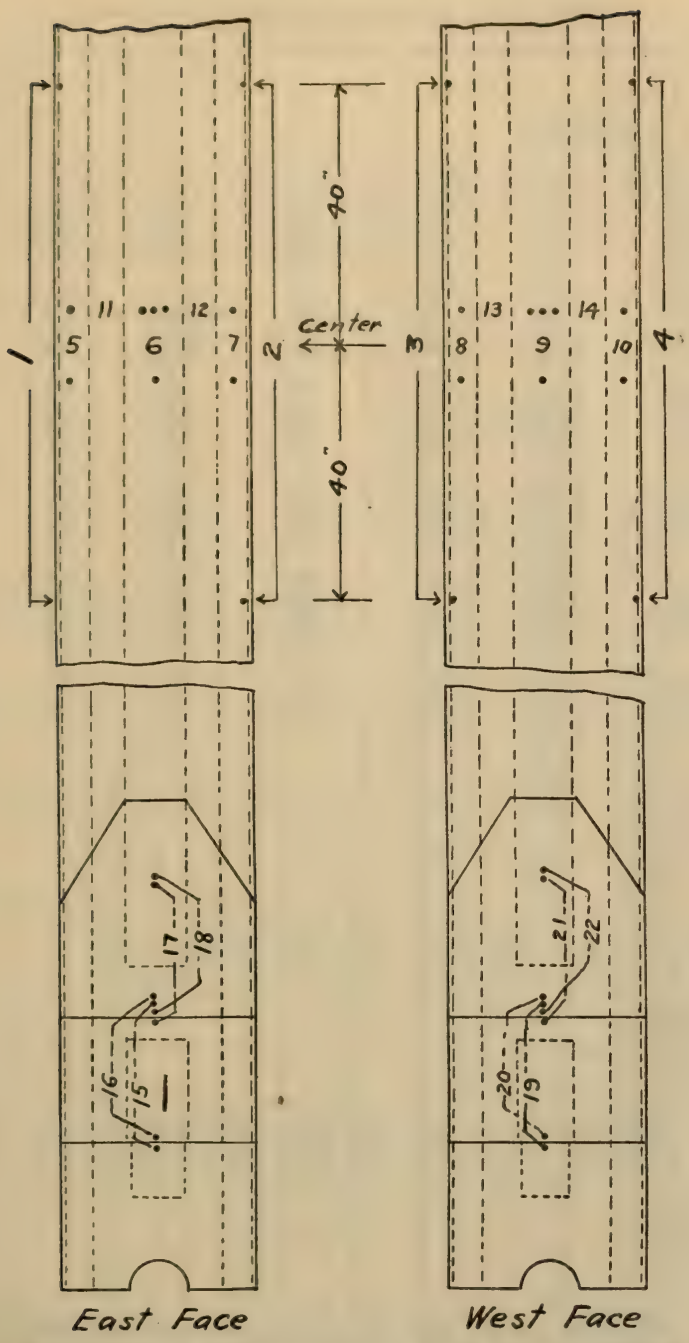


FIG. 8.—*Column 31HC (carbon steel). Key to stations on Table 8*

TABLE 9.—Log of Test, Column 32S, of Silicon Steel

[Cumulative (±) Elongations at Stations Below. Tested July 8, 1914. Time of Test, 10.15 a. m. to 12.30 p. m.]

Load, pounds	Load in pounds per square inch	1	2	3	4	Average, 1 to 4
75 990	1000	0	0	0	0	0
379 950	5000	— .0065	— .0060	— .0150	— .0144	— .0105
759 900	10 000	— .0190	— .0192	— .0285	— .0276	— .0236
1 139 850	15 000	— .0321	— .0322	— .0414	— .0403	— .0365
1 215 840	16 000	— .0351	— .0352	— .0443	— .0430	— .0394
1 291 820	17 000	— .0380	— .0380	— .0469	— .0458	— .0422
1 367 820	18 000	— .0407	— .0410	— .0500	— .0486	— .0451
1 443 810	19 000	— .0430	— .0437	— .0527	— .0510	— .0476
1 519 800	20 000	— .0460	— .0463	— .0554	— .0537	— .0504
1 595 790	21 000	— .0480	— .0487	— .0578	— .0559	— .0526
1 671 780	22 000	— .0507	— .0519	— .0604	— .0588	— .0555
[a] 1 747 770	23 000	— .0537	— .0550	— .0635	— .0618	— .0585
1 823 760	24 000	— .0563	— .0578	— .0665	— .0646	— .0613
1 899 750	25 000	— .0592	— .0608	— .0697	— .0677	— .0644
1 975 740	26 000	— .0620	— .0637	— .0725	— .0704	— .0672
2 051 730	27 000	— .0649	— .0672	— .0757	— .0740	— .0705
2 127 720	28 000	— .0680	— .0706	— .0790	— .0771	— .0737
2 203 710	29 000	— .0714	— .0742	— .0829	— .0804	— .0772
2 279 700	30 000	— .0750	— .0772	— .0861	— .0837	— .0805
[b] 2 279 700	30 000	— .0750	— .0772	— .0863	— .0834	— .0805
[c] 2 431 680	32 000	— .0810	— .0840	— .0929	— .0900	— .0870
2 583 660	34 000	— .0887	— .0919	— .1013	— .0983	— .0951
2 735 640	36 000	— .0964	— .1003	— .1100	— .1067	— .1034
2 887 620	38 000	— .1057	— .1094	— .1203	— .1170	— .1131
3 039 600	40 000	— .1165	— .1208	— .1337	— .1286	— .1249
3 191 580	42 000	— .1309	— .1354	— .1513	— .1454	— .1408
[d] 3 343 560	44 000	— .1515	— .1575	— .1790	— .1725	— .1651
[e] 3 495 540	46 000	— .1945	— .2000	— .2370	— .2325	— .2160
[f] 3 700 700	48 700	.....	.....	.....	.....	[g] — .2986
[h] 3 829 900	50 400	.....	.....	.....	.....	[g] — .3990
[i] 4 020 000	52 800	.....	.....	.....	.....	.....

Load, pounds	Load in pounds per square inch	15	16	17	18	19	20	21	22
75 990	1 000	0	0	0	0	0	0	0	0
759 900	10 000	—.0026	—.0027	—.0035	—.0026	—.0056	—.0039	—.0044	—.0029
1 519 800	20 000	—.0073	—.0063	—.0083	—.0051	—.0116	—.0081	—.0097	—.0049
2 279 700	30 000	—.0139	—.0121	—.0147	—.0069	—.0180	—.0130	—.0156	—.0067

Load, pounds	Load in pounds per square inch	23	24	25	26	27	28	29	30	31	32	33
75 990	1000	0	0	0	0	0	0	0	0	0	0	0
759 900	10 000	+.0012	—.0010	—.0005	+.0010	—.0008	—.0004	+.0007	—.0014	—.0003	+.0006	—.0015
1 519 800	20 000	+.0016	—.0018	—.0014	+.0017	—.0018	—.0014	+.0016	—.0026	—.0010	+.0018	—.0021
2 279 700	30 000	+.0026	—.0029	—.0021	+.0031	—.0028	—.0018	+.0032	—.0034	—.0016	+.0025	—.0030

Load, pounds	Load in pounds per square inch	34	35	36	37	37A	38	39	40	41	42	43
75 990	1000	0	0	0	0	0	0	0	0	0	0	0
759 900	10 000	—.0006	+.0001	—.0033	—.0002	+.0020	+.0006	—.0004	—.0007	+.0006	+.0001	—.0003
1 519 800	20 000	—.0012	+.0011	—.0029	—.0003	+.0039	+.0017	—.0009	—.0019	+.0013	—.0006	—.0009
2 279 700	30 000	—.0022	+.0017	—.0035	—.0014	+.0061	+.0022	—.0015	—.0026	+.0023	—.0013	—.0013

[a] Slight "creaking" sound.
[b] Check readings 17 minutes later.
[c] Pronounced scaling of steel.
[d] Creaking sounds.
[e] Scaling heavily; no deflection.
[f] Column deflects to east $\frac{3}{16}$ inch.
[g] Approximate as read with a scale.
[h] Center web buckling.
[i] Maximum load. Falls off to 3 980 000 and then to 3 910 000. Maximum deflection 2⅞ inches to east.

TABLE 9.—Log of Test, Column 32S, of Silicon Steel—Continued

Load, pounds	Load in pounds per square inch	44	45	46	47	48	49	50	51	52	52A
75 990	1000	0	0	0	0	0	0	0	0	0	0
759 900	10 000	+.0015	−.0002	−.0008	+.0005	−.0006	−.0009	+.0005	.0000	−.0006	+.0022
1 519 800	20 000	+.0020	−.0012	−.0021	+.0019	−.0009	−.0017	+.0012	.0000	−.0009	+.0044
2 279 700	30 000	+.0031	−.0022	−.0024	+.0034	−.0017	−.0033	+.0019	+.0002	−.0023	+.0059

NOTE.—Stations 1 to 4, inclusive, give compressions in inches in gauge length of 80 inches. Other stations give (±) elongations in inches in gauge length of 16 inches.

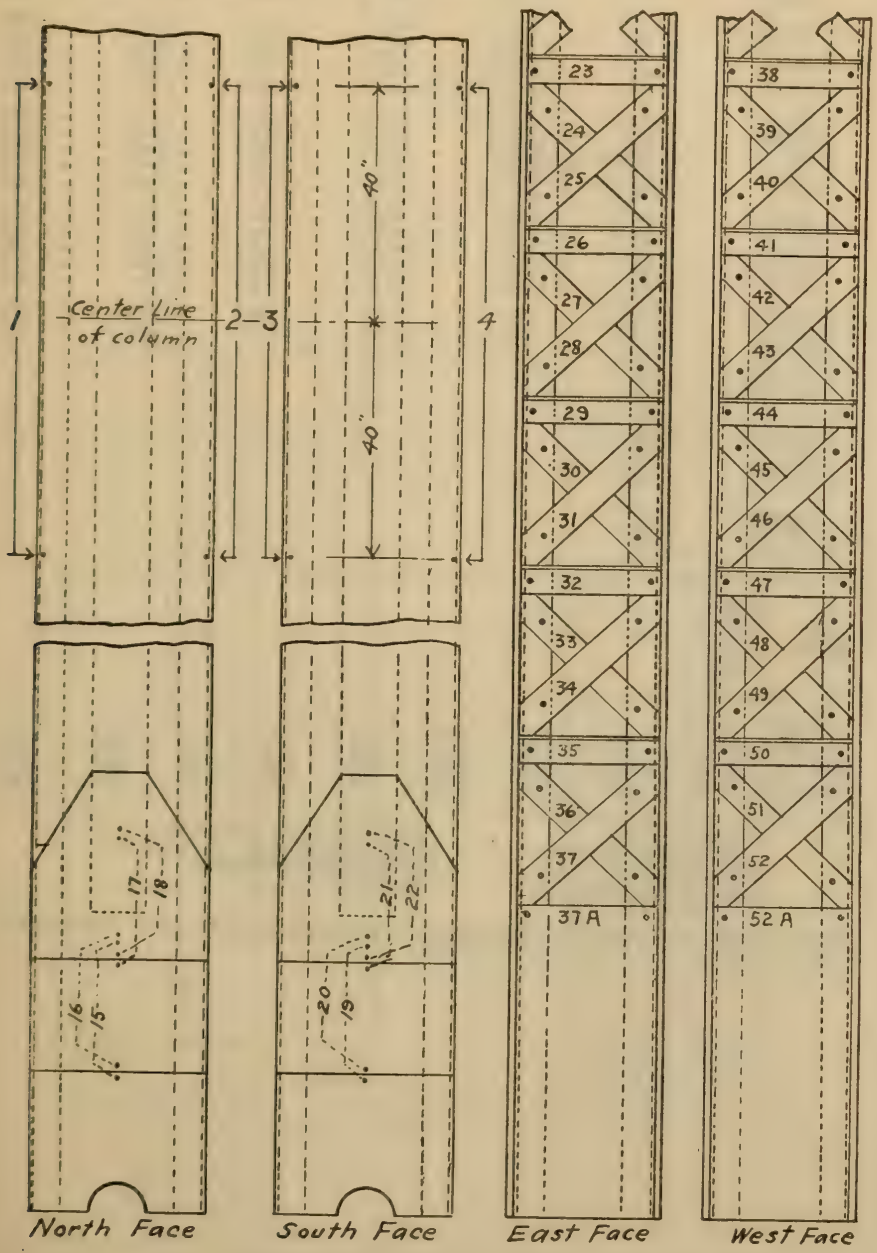


FIG. 9.—*Column 32S (silicon steel). Key to stations on Table 9*

TABLE 10.—Log of Test, Column 34CS, of Chrome Steel

[Cumulative (±) Elongations at Stations Below. Tested July 11, 1914. Time of Test, 9.30 a. m. to 11.12 a. m.]

Load, pounds	Load in pounds per square inch	1	2	3	4	Average, 1 to 4
75 990	1 000	0	0	0	0	0
379 950	5 000	— .0113	— .0087	— .0103	— .0113	— .0104
759 900	10 000	— .0249	— .0225	— .0230	— .0250	— .0239
1 139 850	15 000	— .0387	— .0360	— .0364	— .0390	— .0375
1 519 800	20 000	— .0537	— .0507	— .0505	— .0530	— .0520
1 595 790	21 000	— .0565	— .0537	— .0538	— .0560	— .0550
1 671 780	22 000	— .0600	— .0567	— .0568	— .0588	— .0581
1 747 770	23 000	— .0633	— .0600	— .0600	— .0622	— .0614
1 823 760	24 000	— .0666	— .0630	— .0630	— .0658	— .0646
1 899 750	25 000	— .0698	— .0669	— .0668	— .0694	— .0682
1 975 740	26 000	— .0734	— .0700	— .0701	— .0730	— .0716
2 051 730	27 000	— .0774	— .0737	— .0739	— .0765	— .0754
[a] 2 127 720	28 000	— .0814	— .0773	— .0776	— .0805	— .0792
2 203 710	29 000	— .0853	— .0808	— .0813	— .0847	— .0830
2 279 700	30 000	— .0891	— .0850	— .0856	— .0890	— .0872
[b] 2 431 680	32 000	— .0986	— .0937	— .0944	— .0980	— .0962
2 583 660	34 000	— .1090	— .1034	— .1050	— .1084	— .1065
2 735 640	36 000	— .1220	— .1149	— .1158	— .1222	— .1187
2 887 620	38 000	— .1387	— .1281	— .1310	— .1396	— .1344
3 039 600	40 000	— .1620	— .1466	— .1513	— .1636	— .1559
[c] 3 191 580	42 000	— .2005	— .1763	— .1826	— .2040	— .1909
[d] 3 267 570	43 000	— .2300	— .1963	— .2035	— .2330	— .2157
3 495 540	46 000	.....	.....	.....	.....	.....
[e] 3 527 000	46 400	.....	.....	.....	.....	.....
3 577 000	47 100	.....	.....	.....	.....	.....
3 647 520	48 000	.....	.....	.....	.....	.....
[f] 3 670 000	48 300	.....	.....	.....	.....	.....
3 690 000	48 600	.....	.....	.....	.....	.....
3 715 000	48 900	.....	.....	.....	.....	.....
[g] 3 741 000	49 200	.....	.....	.....	.....	.....
[h] 3 680 000	48 500	.....	.....	.....	.....	.....
3 634 000	47 700	.....	.....	.....	.....	.....
[i] 3 400 000	44 700	.....	.....	.....	.....	.....

Load, pounds	Load in pounds per square inch	15	16	17	18	19	20	21	22
75 990	1 000	0	0	0	0	0	0	0	0
759 900	10 000	— .0028	— .0024	— .0038	— .0028	— .0040	— .0026	— .0045	— .0035
1 519 800	20 000	— .0075	— .0063	— .0093	— .0059	— .0088	— .0071	— .0102	— .0065
2 279 700	30 000	— .0139	— .0110	— .0147	— .0083	— .0144	— .0122	— .0169	— .0090
3 039 600	40 000	— .0225	— .0180	— .0234	— .0109	— .0214	— .0187	— .0243	— .0119

[a] Creaking sounds.
[b] Center diaphragm scaling.
[c] Steel scaling freely.
[d] Center diaphragm buckling.
[e] Lacing begins to buckle.
[f] Center web buckles about ¼ inch.
[g] Load begins to fall off. Maximum load.
[h] Lacing buckles considerably.
[i] Last reading.

NOTE.—Stations 1 to 4, inclusive, give compressions in inches in gauge length of 80 inches. Other stations give compressions in inches in gauge length of 16 inches.

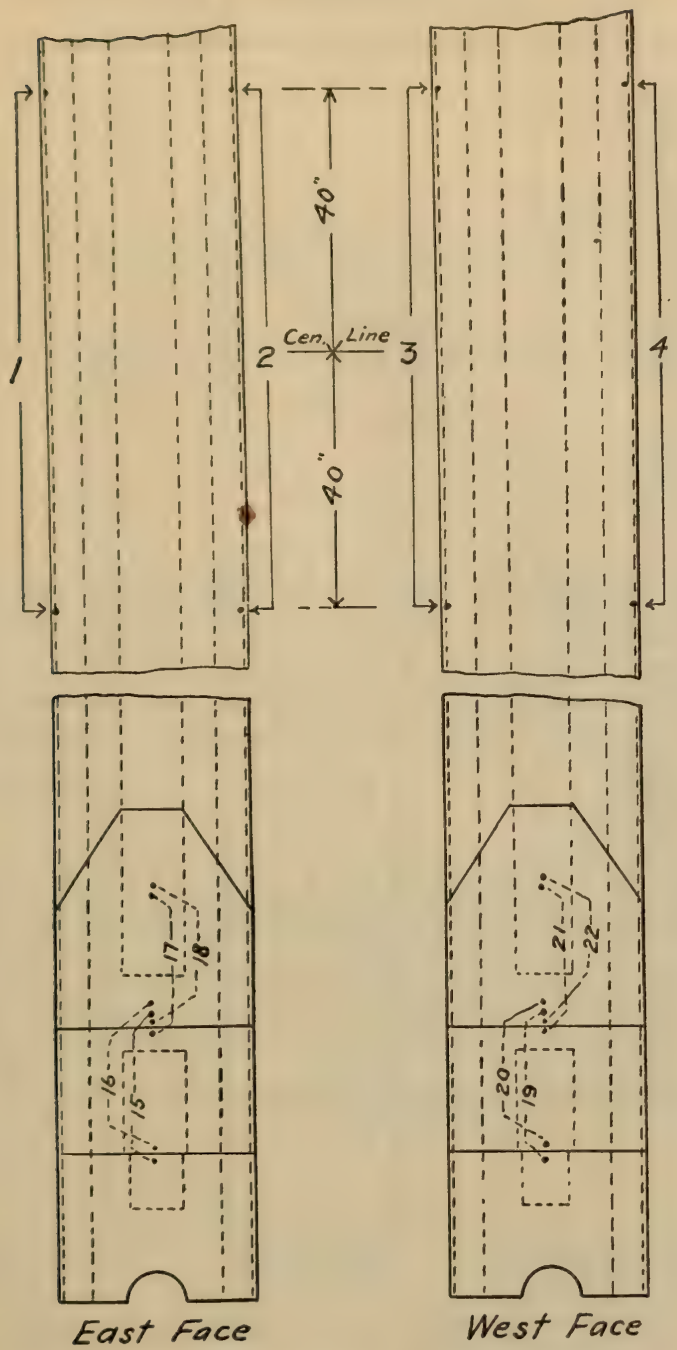


FIG. 10.—*Column 34CS (chrome steel). Key to stations on Table 10*

TABLE 11.—Log of Test, Column HC1, of High Carbon Steel

[Area=76.46 square inches. Cumulative Elongations (±) at Stations Below. Tested Jan. 17, 1914.]

Load, pounds	Load in pounds per square inch	1	2	3	4	5	6	7	8	9	10	11
76 460	1000	0	0	0	0	0	0	0	0	0	0	0
152 920	2000	−.0022	−.0004	−.0029	−.0035	−.0002	−.0024	−.0004	−.0002	−.0007	−.0006	+.0001
382 300	5000	−.0112	−.0014	−.0118	−.0108	−.0008	−.0095	−.0010	−.0033	−.0011	−.0013	−.0019
764 600	10 000	−.0252	−.0028	−.0258	−.0247	−.0022	−.0225	−.0022	−.0044	−.0027	−.0024	−.0042
1 146 900	15 000	−.0389	.....	−.0403	−.0386	.....	−.0363	.....	.....	.....	.....	.....
1 529 200	20 000	−.0535	−.0054	−.0557	−.0537	−.0050	−.0506	−.0047	−.0069	−.0048	−.0057	−.0121
1 928 000	25 200	−.0702	.....	−.0733	−.0699	.....	−.0663	.....	.....	.....	.....	.....
2 293 800	30 000	−.0876	−.0090	−.0915	−.0868	−.0086	−.0825	−.0082	−.0091	−.0081	−.0080	−.0227
2 676 100	35 000	−.1193	.....	−.1197	−.1111	.....	−.1065	.....	.....	.....	.....	.....
3 460 000	[a] 45 300	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
3 220 000	[b]	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....

Load, pounds	Load in pounds per square inch	12	13	14	15	16	17	18	19	20	21	22
76 460	1000	0	0	0	0	0	0	0	0	0	0	0
152 920	2000	−.0008	−.0004	−.0024	−.0002	−.0012	−.0003	−.0006	−.0014	+.0006	+.0008	+.0024
382 300	5000	−.0028	−.0029	−.0040	−.0008	−.0014	+.0002	−.0004	−.0016	−.0004	+.0002	+.0022
764 600	10 000	−.0061	−.0070	−.0069	−.0019	−.0022	−.0002	−.0012	−.0014	−.0016	−.0011	+.0002
1 146 900	15 000	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
1 529 200	20 000	−.0144	−.0141	−.0139	−.0043	−.0020	−.0008	−.0012	−.0018	−.0043	−.0036	−.0038
1 928 000	25 200	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
2 293 800	30 000	−.0240	−.0248	−.0238	−.0264	−.0014	−.0013	−.0016	−.0020	−.0066	−.0074	−.0056

Load, pounds	Load in pounds per square inch	23	24	25	26	27	28	29	30	31	32
76 460	1000	0	0	0	0	0	0	0	0	0	0
152 920	2000	+.0033	+.0001	+.0002	+.0004	−.0003	−.0005	−.0006	0	−.0011	−.0004
382 300	5000	+.0008	−.0001	0	+.0004	−.0001	−.0002	−.0002	0	−.0017	−.0005
764 600	10 000	−.0012	0	−.0004	+.0005	+.0006	−.0002	+.0002	+.0004	−.0027	−.0013
1 146 900	15 000	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
1 529 200	20 000	−.0026	−.0010	−.0016	+.0001	+.0014	+.0007	−.0008	+.0010	−.0037	−.0041
1 928 000	25 200	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
2 293 800	30 000	−.0062	−.0020	−.0020	−.0004	+.0008	+.0004	+.0018	+.0016	−.0055	−.0063

[a] Maximum load. Column buckled to west 4 inches. [b] Load fell off to 3 220 000 pounds.

NOTE.—Stations 1, 3, 4, and 6 give compressions in inches in gauge length of 80 inches. Other stations give (±) elongations in inches in gauge length of 8 inches.

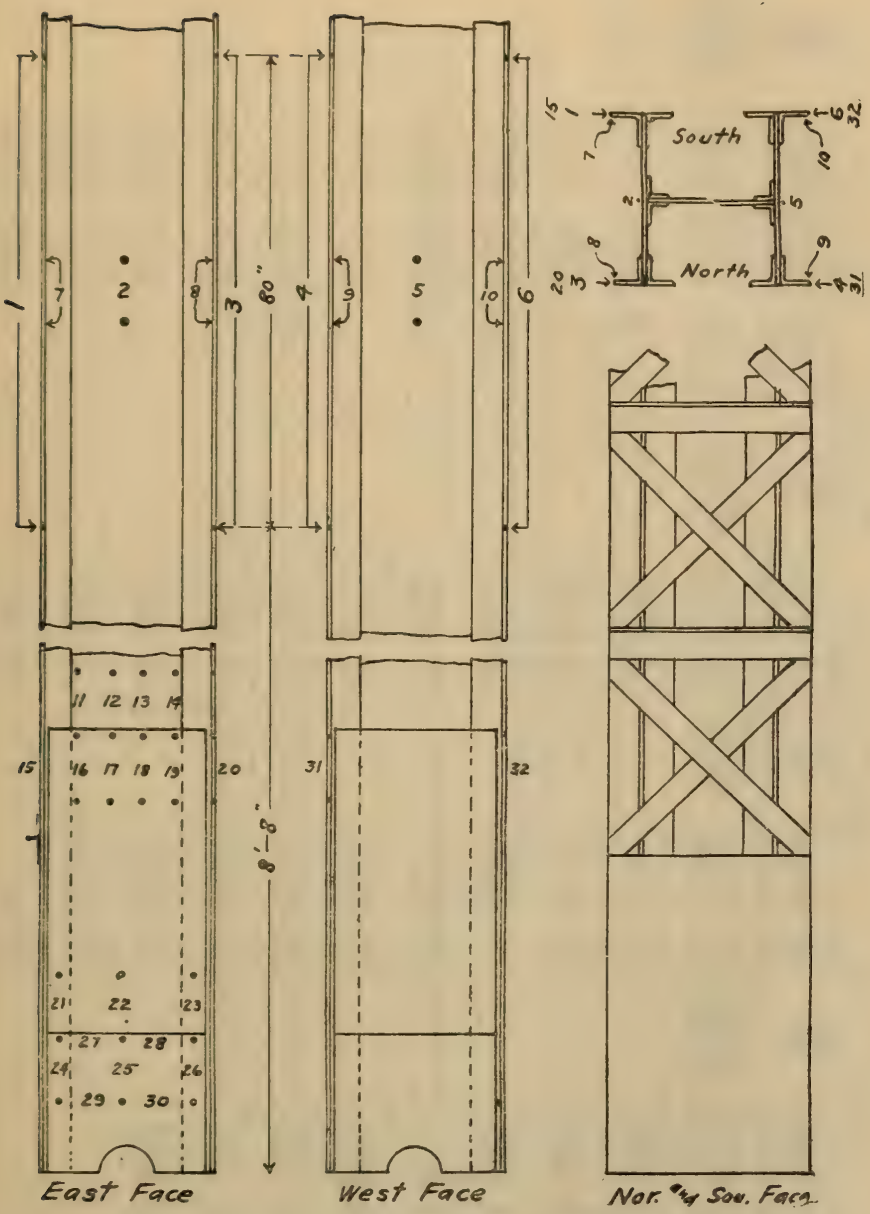


FIG. 11.—*Column HC1 (carbon steel). Key to stations on Table 11*

TABLE 12.—Log of Test, Column MY1, of Mayari Steel

[Area=76.46. Cumulative (±) Elongations at Stations Below. Tested Jan. 15, 1914.]

Load, pounds	Load in pounds per square inch	1	2	3	4	5	6	7	8	9	10
76 460	1000	0	0	0	0	0	0	0	0	0	0
382 300	5000	−.0112	−.0012	−.0100	−.0083	−.0012	−.0111	+.0022	−.0021	−.0009	−.0004
764 600	10 000	−.0252	−.0026	−.0227	−.0211	−.0021	−.0241	−.0018	−.0036	−.0020	−.0008
1 146 900	15 000	−.0391	−.0042	−.0360	−.0338	−.0039	−.0374	−.0016	−.0050	−.0032	−.0032
1 529 200	20 000	−.0519	−.0052	−.0486	−.0456	−.0046	−.0502	−.0018	−.0060	−.0046	−.0046
1 911 500	25 000	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
2 293 800	30 000	−.0794	−.0084	−.0758	−.0722	−.0081	−.0786	−.0063	−.0087	−.0074	−.0072
2 676 100	35 000	−.0937	−.0100	−.0909	−.0854	−.0094	−.0932	−.0098	−.0100	−.0088	−.0082
3 058 400	40 000	−.1085	−.0116	−.1055	−.0987	−.0110	−.1081	−.0080	−.0112	−.0102	−.0096
3 440 700	45 000	−.1252	−.0134	−.1219	−.1127	−.0128	−.1239	−.0098	−.0128	−.0117	−.0118
3 823 000	50 000	−.1460	.....	−.1423	−.1279	.....	−.1428	(a)	.....	.....	.....
4 205 300	55 000	−.2011	.....	−.1895	−.1566	.....	−.1811	.....	.....	.....	.....
[b]4 700 000	61 400	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
4 800 000	62 800	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
[c]4 934 100	64 700	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
[d]2 520 000	33 000	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....

Load, pounds	Load in pounds per square inch	37	38	39	40	41	42	43	44	45	46
76 460	1000	0	0	0	0	0	0	0	0	0	0
382 300	5000	+.0004	+.0010	+.0002	+.0010	+.0008	0	−.0001	−.0016	−.0002	+.0001
764 600	10 000	+.0004	+.0006	+.0008	+.0008	−.0016	+.0001	+.0002	−.0003	+.0002	+.0006
1 146 900	15 000	+.0008	+.0008	+.0006	+.0022	−.0008	+.0002	+.0006	−.0004	+.0009	+.0005
1 529 200	20 000	+.0010	+.0011	+.0008	+.0031	−.0002	+.0004	+.0005	−.0003	+.0010	+.0007
2 293 800	30 000	+.0014	+.0018	+.0008	+.0034	+.0008	+.0006	+.0011	−.0002	+.0014	+.0008
3 058 400	40 000	+.0016	+.0020	+.0004	+.0034	+.0010	+.0012	+.0014	−.0002	+.0018	+.0009

Load, pounds	Load in pounds per square inch	47	48	49	50	51	52	53	54	55	56
76 140	1000	0	0	0	0	0	0	0	0	0	0
382 300	5000	+.0008	+.0007	+.0019	+.0011	−.0001	+.0006	+.0007	+.0008	+.0005	0
764 600	10 000	+.0012	.....	+.0015	+.0005	+.0023	+.0007	+.0005	+.0013	+.0007	0
1 146 900	15 000	+.0016	+.0008	+.0015	+.0012	+.0011	+.0010	+.0007	+.0022	+.0006	+.0002
1 529 200	20 000	+.0022	+.0010	+.0017	+.0012	+.0015	+.0014	+.0009	+.0014	+.0012	+.0003
2 293 800	30 000	+.0032	+.0013	+.0031	+.0014	+.0021	+.0020	+.0009	+.0016	+.0017	+.0013
3 058 400	40 000	+.0046	+.0015	+.0031	+.0017	+.0025	+.0022	+.0017	+.0016	+.0022	+.0014

Load, pounds	Load in pounds per square inch	57	58	59	60	61	62	63	64
76 140	1000	0	0	0	0	0	0	0	0
382 300	5000	+.0003	+.0001	+.0004	+.0002	−.0010	−.0012	−.0008	−.0010
764 600	10 000	+.0004	+.0004	+.0008	.....	−.0022	−.0020	−.0030	−.0020
1 146 900	15 000	+.0007	+.0006	+.0012	.....	−.0030	−.0030	−.0041	−.0032
1 529 200	20 000	+.0011	+.0010	+.0018	+.0005	−.0039	−.0040	−.0051	−.0033
2 293 800	30 000	+.0017	+.0018	+.0030	+.0008	−.0054	−.0060	−.0074	−.0066
2 676 100	35 000	.....	.....	.....	.....	−.0072	−.0073	−.0085	−.0077
3 058 400	40 000	+.0022	+.0028	+.0048	+.0008	−.0082	−.0086	−.0097	−.0089
3 440 700	45 000	.....	.....	.....	.....	−.0094	−.0099	−.0110	−.0103

[a] The initial reading may have been in error. The observer complained of bad holes for gauge points.
[b] Primary failure. Buckling to west 2 inches.
[c] Maximum load.
[d] Load fell to 2 520 000. Total deflection to west, 7¾ inches; to north, 1¼ inches.

NOTE.—Stations 1, 3, 4, and 6 give compressions in inches in gauge lengths of 80 inches. Other stations give (±) elongations in inches in gauge lengths of 8 inches.

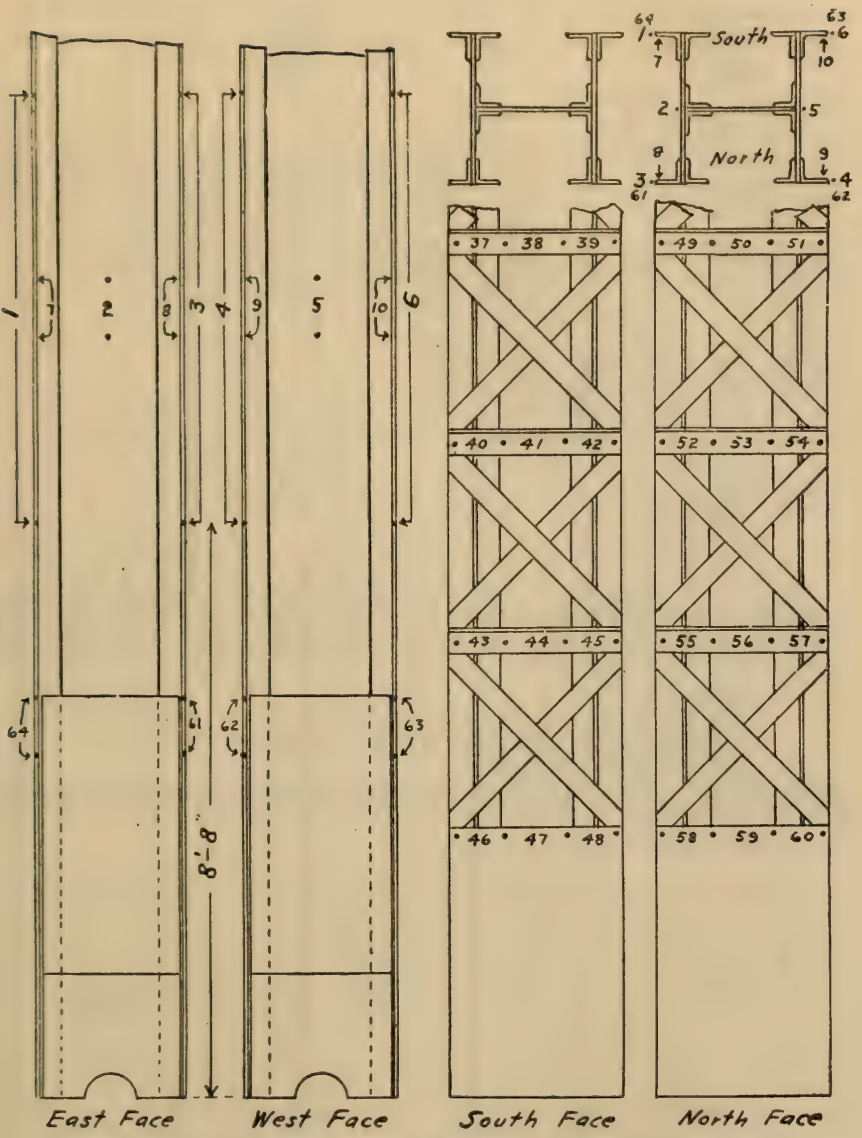


FIG. 12.—*Column MY1 (Mayari steel). Key to stations on Table 12*

TABLE 13.—Log of Test, Column 31HC1, Carbon Steel

[Cumulative (±) Elongation at Stations Below. Tested July 10, 1914. Time of test, 10.02 a. m. to 12 m.]

Load, pounds	Load in pounds per square inch	1	2	3	4	Load, pounds	Load in pounds per square inch	1	2	3	4
76 260	1000	0	0	0	0			0	0	0	0
381 300	5000	−.0084	−.0077	−.0127	−.0143	2 440 320	32 000	−.0935	−.0927	−.0995	−.1003
762 600	10 000	−.0211	−.0212	−.0268	−.0283	[a] 2 592 840	34 000	−.1040	−.1027	−.1109	−.1111
991 380	13 000	−.0293	−.0296	−.0350	−.0365	2 745 360	36 000	−.1169	−.1152	−.1247	−.1250
1 067 640	14 000	−.0320	−.0320	−.0377	−.0391	2 897 880	38 000	−.1350	−.1330	−.1446	−.1447
1 143 900	15 000	−.0344	−.0350	−.0408	−.0422	3 050 400	40 000	−.1632	−.1599	−.1753	−.1754
1 220 160	16 000	−.0374	−.0381	−.0434	−.0451	3 202 920	42 000	−.2004	−.1987	−.2539	.....
1 296 420	17 000	−.0403	−.0407	−.0463	−.0477	[b] 3 355 440	44 000	.....	.....	.....	.....
1 372 680	18 000	−.0430	−.0437	−.0490	−.0505	[c] 3 507 960	46 000	.....	.....	.....	.....
1 448 940	19 000	−.0460	−.0462	−.0520	−.0533	[d] 3 550 000	46 550	.....	.....	.....	.....
1 525 200	20 000	−.0490	−.0490	−.0553	−.0564						
1 677 720	22 000	−.0550	−.0553	−.0613	−.0627						
1 830 240	24 000	−.0618	−.0620	−.0675	−.0687						
1 982 760	26 000	−.0684	−.0685	−.0750	−.0757						
2 135 280	28 000	−.0769	−.0761	−.0823	−.0835						
2 287 800	30 000	−.0843	−.0836	−.0906	−.0918						

Load, pounds	Load in pounds per square inch	15	16	17	18	19	20	21	22	23	24
76 260	1000	0	0	0	0	0	0	0	0	0	0
762 600	10 000	−.0023	−.0017	−.0066	−.0043	−.0024	−.0021	−.0078	−.0051	−.0022	+.0011
1 525 200	20 000	−.0060	−.0042	−.0164	−.0102	−.0068	−.0050	−.0186	−.0111	−.0052	+.0020
2 287 800	30 000	−.0103	−.0071	−.0308	−.0181	−.0114	−.0078	−.0332	[e]	−.0089	+.0030
3 050 400	40 000	−.0157	−.0098	−.0819	−.0374	−.0180	−.0106	−.0862	.....	−.0142	+.0045

[a] Scaling freely.
[b] Maximum deflection ⅛ inch to east.
[c] Center web buckling. Column deflects to north. Deflection to east disappearing.
[d] Maximum load. Deflection, 5 inches to north at 3 430 000.
[e] Movement beyond range of gauge.

NOTE.—Stations 1 to 4, inclusive, give compressions in inches in gauge length of 80 inches. Stations 15 to 22 give compressions in inches in gauge length of 16 inches. Stations 23 and 24 give (±) elongations in inches in gauge length of 8 inches.

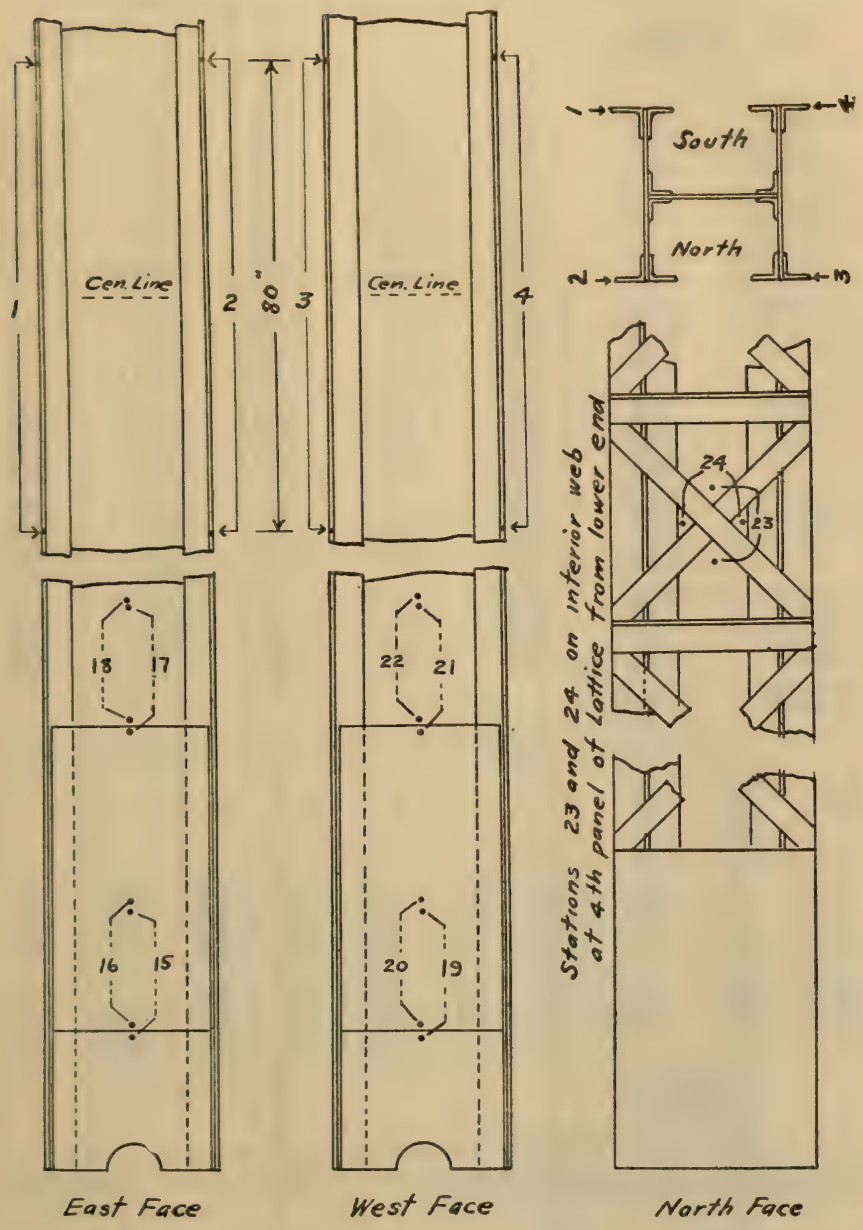


FIG. 13.—*Column 31HC1 (carbon steel). Key to stations on Table 13*

TABLE 14.—Log of Test, Column 32S1, of Silicon Steel

[Cumulative (±) Elongations at Stations Below. Tested July 9, 1914. Time of Test, 10.29 a. m. to 12.16 p. m.]

Load, pounds	Load in pounds per square inch	1	2	3	4	Average, 1 to 4
76 260	1000	0.0000	—0.0000	0.0000	0.0000	0.0000
381 300	5000	— .0084	— .0156	— .0119	— .0061	— .0105
762 600	10 000	— .0208	— .0319	— .0261	— .0168	— .0239
76 260	1000	— .0002	+ .0002	+ .0002	— .0002	.0000
762 600	10 000	— .0213	— .0323	— .0264	— .0172	— .0243
1 143 900	15 000	— .0342	— .0470	— .0404	— .0285	— .0375
1 220 160	16 000	— .0366	— .0500	— .0430	— .0313	— .0402
1 296 400	17 000	— .0395	— .0530	— .0456	— .0337	— .0430
1 372 700	18 000	— .0423	— .0557	— .0483	— .0363	— .0457
1 448 940	19 000	— .0450	— .0588	— .0513	— .0388	— .0485
1 525 200	20 000	— .0478	— .0620	— .0545	— .0413	— .0514
1 601 460	21 000	— .0503	— .0653	— .0574	— .0437	— .0542
1 677 720	22 000	— .0532	— .0683	— .0600	— .0463	— .0570
[a] 1 753 980	23 000	— .0563	— .0712	— .0630	— .0492	— .0599
1 830 240	24 000	— .0593	— .0747	— .0660	— .0523	— .0631
1 906 500	25 000	— .0623	— .0784	— .0695	— .0549	— .0663
76 260	1000	— .0012	— .0049	— .0027	— .0004	— .0023
[b] 1 906 500	25 000	— .0623	— .0787	— .0693	— .0549	— .0663
1 982 760	26 000	— .0650	— .0819	— .0721	— .0573	— .0691
2 135 280	28 000	— .0713	— .0884	— .0785	— .0629	— .0753
2 287 800	30 000	— .0780	— .0963	— .0858	— .0694	— .0824
2 440 320	32 000	— .0850	— .1043	— .0934	— .0755	— .0896
2 592 840	34 000	— .0930	— .1133	— .1014	— .0827	— .0976
2 745 360	36 000	— .1005	— .1230	— .1100	— .0904	— .1060
2 897 880	38 000	— .1090	— .1345	— .1198	— .0985	— .1155
3 050 400	40 000	— .1190	— .1464	— .1308	— .1072	— .1259
[c] 3 202 900	42 000	— .1308	— .1617	— .1460	— .1185	— .1393
3 355 440	44 000	— .1458	— .1812	— .1634	— .1330	— .1559
3 507 960	46 000	— .1670	— .2089	— .1890	— .1542	— .1798
3 660 480	48 000	— .1992	— .2524	— .2354	— .1830	— .2175
[d] 3 813 000	50 000	.....	.....	.....	.....	.....
[e] 3 949 000	51 700	.....	.....	.....	.....	.....

Load, pounds	Load in pounds per square inch	15	16	17	18	19	20	21	22
76 260	1000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
762 600	10 000	— .0032	— .0023	— .0073	— .0060	— .0029	— .0027	— .0077	— .0050
76 260	1000	— .0000	+ .0003	— .0001	+ .0001	+ .0005	+ .0002	— .0004	+ .0003
762 600	10 000	— .0032	— .0022	— .0069	— .0052	— .0025	— .0025	— .0073	— .0044
1 143 900	15 000	— .0048	— .0035	— .0112	— .0079	— .0040	— .0035	— .0121	— .0072
1 525 200	20 000	— .0070	— .0050	— .0165	— .0108	— .0060	— .0046	— .0178	— .0102
1 906 500	25 000	— .0090	— .0064	— .0225	— .0139	— .0084	— .0061	— .0242	— .0134
76 260	1000	— .0003	+ .0005	— .0031	— .0004	+ .0004	+ .0007	— .0036	.0000
1 906 500	25 000	— .0093	— .0064	— .0227	— .0136	— .0083	— .0060	— .0243	— .0133

[a] Scaling slightly.
[b] Creaking.
[c] Scaling freely.
[d] Center web buckling.
[e] Maximum load. Load falls off. 4 by 4 inch L's buckling at lacing points.

NOTE.—Stations 1 to 4, inclusive, give compressions in inches in gauge length of 80 inches. Other stations give (±) elongations in inches in gauge length of 16 inches.

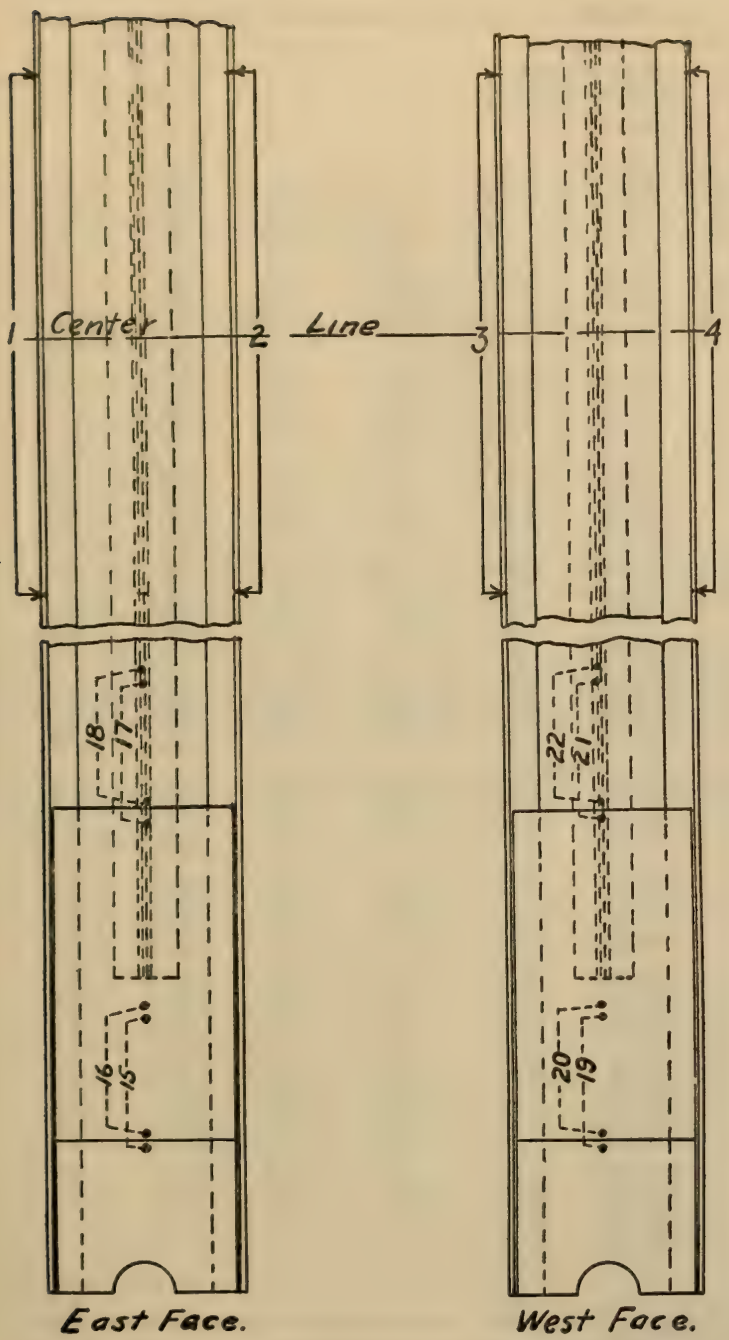


FIG. 14.—*Column 32S1 (silicon steel). Key to stations on Table 14*

TABLE 15.—Log of Test, Column 34CS1, of Chrome Steel

[Cumulative (±) Elongations at Stations Below. Tested July 13–14, 1914]

Time	Load, pounds	Load in pounds per square inch	1	2	3	4	Average, 1 to 4
July 13:							
2.20	76 260	1000	0	0	0	0	0
2.25	381 300	5000	−.0124	−.0071	−.0083	−.0130	−.0102
2.30	762 600	10 000	−.0262	−.0196	−.0208	−.0273	−.0235
	1 143 900	15 000	−.0400	−.0330	−.0343	−.0410	−.0371
2.46	76 260	1000	−.0007	−.0001	−.0009	−.0018	−.0009
3.00	381 300	5000	−.0132	−.0077	−.0094	−.0142	−.0111
3.03	762 600	10 000	−.0272	−.0206	−.0217	−.0280	−.0244
3.14	1 143 900	15 000	−.0408	−.0337	−.0348	−.0413	−.0377
	1 525 200	20 000	−.0557	−.0477	−.0487	−.0556	−.0519
	1 601 460	21 000	−.0592	−.0510	−.0517	−.0586	−.0551
	1 677 720	22 000	−.0623	−.0540	−.0543	−.0610	−.0579
	1 753 980	23 000	−.0657	−.0570	−.0576	−.0644	−.0612
	1 830 240	24 000	−.0690	−.0597	−.0608	−.0680	−.0644
	[a] 1 906 500	25 000	−.0730	−.0630	−.0640	−.0714	−.0679
3.41	76 260	1000	−.0060	−.0032	−.0043	−.0064	−.0050
3.43	381 300	5000	−.0182	−.0112	−.0133	−.0189	−.0154
	762 600	10 000	−.0321	−.0244	−.0257	−.0324	−.0287
3.50	1 143 900	15 000	−.0459	−.0377	−.0384	−.0450	−.0418
	1 525 200	20 000	−.0594	−.0505	−.0510	−.0582	−.0548
4.00	1 906 500	25 000	−.0733	−.0633	−.0642	−.0717	−.0681
4.12	[b] 76 260	1000	−.0064	−.0033	−.0047	−.0068	−.0053
July 14:							
9.36	86 000	1130	−.0104	−.0079	−.0098	−.0108	−.0097
9.45	76 260	1000	−.0100	−.0082	−.0102	−.0105	−.0097
10.18	381 300	5000	−.0229	−.0163	−.0177	−.0234	−.0201
10.22	762 600	10 000	−.0360	−.0290	−.0306	−.0370	−.0332
	1 143 900	15 000	−.0498	−.0424	−.0434	−.0497	−.0463
	1 525 200	20 000	−.0635	−.0557	−.0559	−.0623	−.0594
10.53	1 601 460	21 000	−.0662	−.0580	−.0586	−.0650	−.0620
	1 677 720	22 000	−.0689	−.0604	−.0613	−.0680	−.0647
10.55	1 753 980	23 000	−.0717	−.0631	−.0637	−.0707	−.0673
10.56	1 830 240	24 000	−.0744	−.0659	−.0662	−.0732	−.0699
10.57	1 906 500	25 000	−.0773	−.0687	−.0686	−.0760	−.0727
10.58	1 982 760	26 000	−.0802	−.0706	−.0713	−.0785	−.0752
11.00	2 059 020	27 000	−.0834	−.0750	−.0749	−.0821	−.0789
11.02	2 135 280	28 000	−.0873	−.0781	−.0782	−.0858	−.0824
11.04	2 211 540	29 000	−.0914	−.0820	−.0817	−.0898	−.0862
11.06	[c] 2 287 800	30 000	−.0955	−.0857	−.0853	−.0934	−.0900
11.20	76 260	1000	−.0153	−.0119	−.0140	−.0157	−.0142
	381 300	5000	−.0281	−.0205	−.0214	−.0280	−.0245
	762 600	10 000	−.0417	−.0336	−.0347	−.0418	−.0380
	1 143 900	15 000	−.0552	−.0464	−.0476	−.0545	−.0509
11.33	1 525 200	20 000	−.0688	−.0594	−.0604	−.0673	−.0640
11.40	1 906 500	25 000	−.0825	−.0730	−.0731	−.0807	−.0773
11.46	2 287 800	30 000	−.0967	−.0866	−.0861	−.0942	−.0909
11.50	[d] 2 440 320	32 000	−.1038	−.0931	−.0932	−.1018	−.0980
11.53	2 592 840	34 000	−.1131	−.1012	−.1011	−.1104	−.1065
11.56	[e] 2 745 360	36 000	−.1248	−.1113	−.1111	−.1214	−.1172
	2 897 880	38 000	−.1376	−.1230	−.1206	−.1337	−.1287
	[f] 3 050 400	40 000	−.1560	−.1380	−.1338	−.1499	−.1444
12.20	3 202 900	42 000	−.1780	−.1559	−.1507	−.1697	−.1636
	3 279 160	43 000	−.1917	−.1673	−.1619	−.1833	−.1761
	3 355 440	44 000	−.2115	−.1824	−.1749	−.2011	−.1925
12.30	3 431 680	45 000	−.2341	−.1999	−.1909	−.2237	−.2122
	[g] 3 876 000	50 800	.....	.....	.....	.....	.....
	[h] 3 948 000	51 800	.....	.....	.....	.....	.....
	[i] 3 920 000	51 400	.....	.....	.....	.....	.....

[a] No deflection visible.
[b] This load was left overnight and on the following morning corresponding readings were as below.
[c] Scaling of center web.
[d] Deflection of 0.005 inch north.
[e] Column scaling.
[f] Center web buckling. Deflection, 0.05 inch north.
[g] Lacing buckles.
[h] Maximum load. Load falls off.
[i] Last reading.

TABLE 15.—Log of Test, Column 34CS1, of Chrome Steel—Continued

Time	Load, pounds	Load in pounds per square inch	15	16	17	18	19	20	21	22
July 13:										
2.10	76 260	1000	0	0	0	0	0	0	0	0
2.35	762 600	10 000	−.0042	−.0027	−.0074	−.0049	−.0036	−.0024	−.0076	−.0054
2.50	76 260	1000	−.0011	−.0001	−.0011	−.0002	−.0009	−.0002	−.0021	−.0004
3.10	762 600	10 000	−.0042	−.0029	−.0085	−.0052	−.0042	−.0024	−.0091	−.0053
	1 525 200	20 000	−.0086	−.0059	−.0184	−.0110	−.0083	−.0059	−.0192	−.0110
July 14:										
10.14	76 260	1000	−.0010	+.0004	−.0042	−.0007	−.0010	.0000	−.0051	−.0007
10.30	762 600	10 000	−.0043	−.0022	−.0108	−.0054	−.0034	−.0026	−.0124	−.0057
10.48	1 525 200	20 000	−.0079	−.0050	−.0199	−.0109	−.0079	−.0057	−.0213	−.0111
11.14	2 287 800	30 000	−.0120	−.0077	−.0311	−.0175	−.0118	−.0076	−.0326	−.0175
12.11	3 050 400	40 000	−.0174	−.0100	−.0509	−.0290	−.0181	−.0107	−.0562	−.0292

Time	Load, pounds	Load in pounds per square inch	26	27	28	29	30	31	32	33	34
July 13:											
2.13	76 260	1000	0	0	0	0	0	0	0	0	0
2.30	762 600	10 000	+.0006	−.0018	−.0016	+.0008	−.0022	−.0013	+.0005	−.0020	−.0015
2.48	76 260	1000	−.0006	+.0003	.0000	+.0002	.0000	.0000	+.0002	.0000	−.0001
3.04	762 600	10 000	+.0003	−.0016	−.0018	+.0008	−.0021	−.0018	+.0014	−.0021	−.0013
3.20	1 525 200	20 000	+.0013	−.0036	−.0035	+.0013	−.0044	−.0034	+.0014	−.0043	−.0032
July 14:											
10.06	76 260	1000	−.0003	−.0004	−.0005	−.0003	−.0004	−.0003	.0000	+.0009	+.0010
10.24	762 600	10 000	+.0012	−.0016	−.0015	+.0009	−.0018	−.0014	+.0012	−.0012	−.0006
10.40	1 525 200	20 000	+.0023	−.0031	−.0029	+.0020	−.0035	−.0027	+.0021	−.0037	−.0023
11.08	2 287 800	30 000	+.0031	−.0049	−.0042	+.0033	−.0053	−.0039	+.0034	−.0054	−.0036
12.09	3 050 400	40 000	+.0056	−.0067	−.0054	+.0041	−.0072	−.0056	+.0046	−.0068	−.0051

NOTE.—Stations 1 to 4 give compressions in inches in gauge length of 80 inches. Stations 15 to 22, inclusive give relative compressions in gauge lengths of 16 inches for various repetitions of loadings and referred to a common origin.

TABLE 15.—Log of Test, Column 34CS1, of Chrome Steel—Continued

Time	Load, pounds	Load in pounds per square inch	35	36	37	37A	41	42	43	44	45
July 13[a]	76 260	1000	0	0	0	0	0	0	0	0	0
	762 600	10 000	+.0003	−.0017	−.0012	+.0016	+.0008	−.0016	−.0012	+.0011	−.0016
	76 260	1000	−.0002	.0000	−.0004	+.0004	+.0004	.0000	+.0001	+.0001	−.0002
	762 600	10 000	−.0001	−.0014	−.0016	+.0016	+.0007	−.0013	−.0013	+.0009	−.0018
	1 525 200	20 000	+.0016	−.0029	−.0026	+.0031	+.0015	−.0036	−.0030	+.0019	−.0037
July 14[a]	76 260	1000	+.0004	+.0004	+.0003	+.0015	−.0002	−.0004	.0000	−.0001	−.0004
	762 600	10 000	+.0006	−.0007	−.0007	+.0025	+.0018	−.0012	−.0007	+.0017	−.0016
	1 525 200	20 000	+.0018	−.0020	−.0019	+.0041	+.0024	−.0029	−.0023	+.0027	−.0034
	2 287 800	30 000	+.0029	−.0035	−.0030	+.0058	+.0034	−.0046	−.0037	+.0039	−.0053
	3 050 400	40 000	+.0037	−.0051	−.0035	+.0082	+.0048	−.0058	−.0051	+.0048	−.0072

Time	Load, pounds	Load in pounds per square inch	46	47	48	49	50	51	52	52A
July 13[a]	76 260	1000	0	0	0	0	0	0	0	0
	762 600	10 000	−.0009	+.0015	−.0017	−.0014	+.0001	−.0006	−.0011	+.0013
	76 260	1000	−.0001	+.0001	−.0002	−.0006	−.0001	+.0005	−.0006	−.0002
	762 600	10 000	−.0018	+.0008	−.0016	−.0016	+.0003	−.0004	−.0016	+.0012
	1 525 200	20 000	−.0032	+.0014	−.0040	−.0030	+.0018	−.0014	−.0029	+.0028
July 14[a]	76 260	1000	−.0001	−.0002	(b)	+.0008	+.0003	+.0014	−.0003	+.0004
	762 600	10 000	−.0010	+.0018	.....	−.0010	+.0010	+.0003	−.0012	+.0018
	1 525 200	20 000	−.0028	+.0024	.....	−.0023	+.0020	−.0006	−.0023	+.0036
	2 287 800	30 000	−.0039	+.0037	.....	−.0035	+.0033	−.0022	−.0029	+.0053
	3 050 400	40 000	−.0051	+.0046	.....	−.0045	+.0041	−.0034	−.0040	+.0079

[a] Time approximately the same as for stations 26–34.
[b] Last run for bar 48 rejected on account of doubtful initial reading.

NOTE.—Stations 26 to 52A on lattice bars give (±) elongations in inches in gauge length of 16 inches for repetitions of loadings as shown in order to show effect on lattice bars.

CHECK READINGS, STATIONS 1 TO 4

[8-inch Berry Guage on Outer Point of Angles at Center of 80-inch Rods]

Time	Load, pounds	Load in pounds per square inch	1	2	3	4	
July 13:							
4.45.....	76 260	1000	0.0198	0.0276	0.0184	0.0142	Standard bar 0.0288
July 14:							
9.35.....	86 000	1130	.0198	.0276	.0185	.0143	Standard bar 0.0289
9.45.....	76 260	1000	.0198	.0277	.0186	.0141	Standard bar 0.0289

NOTE.—Stations 1 to 4 give compressions in inches in gauge length of 80 inches for various repetitions of loadings.

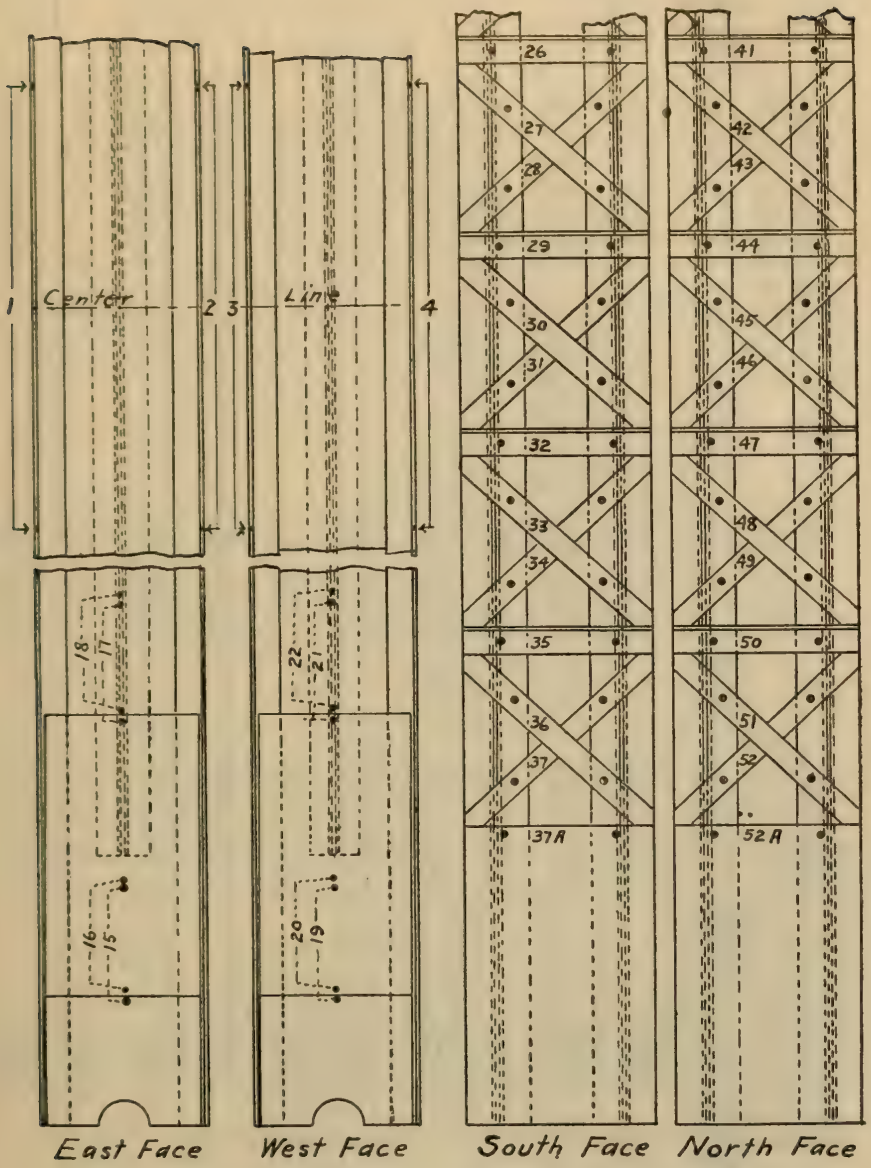


FIG. 15.—*Column 34CS1 (chrome steel). Key to stations on Table 15*

TABLE 16.—Log of Test, Column US_2MS_1, Carbon Steel

[Cumulative (±) Elongations at Stations Below. Tested Jan. 27, 1914. Time of Test, 10 a. m. to 12 m.]

Load, pounds	Load in pounds per square inch	1	2	3	4	5	6	7	8	9	10
55 170	1000	0	0	0	0	0	0	0	0	0	0
275 850	5000	−.0110	−.0045	−.0087	−.0163	−.0014	−.0007	−.0011	−.0014	−.0022	−.0012
551 700	10 000	−.0263	−.0145	−.0207	−.0335	−.0029	−.0021	−.0024	−.0030	−.0032	−.0027
827 550	15 000	−.0429	−.0270	−.0332	−.0507	−.0051	−.0035	−.0033	−.0046	−.0050	−.0047
965 500	17 500	−.0525	−.0331	−.0396	−.0600	.....	.....	.....	.....	.....	.....
1 103 400	20 000	−.0620	−.0400	−.0464	−.0699	−.0072	−.0051	−.0050	−.0068	−.0076	−.0061
1 241 300	22 500	−.0730	−.0467	−.0538	−.0807	.....	.....	.....	.....	.....	.....
1 379 250	25 000	−.0860	−.0546	−.0609	−.0934	−.0103	−.0065	−.0062	−.0090	−.0100	−.0084
1 517 200	27 500	−.1000	−.0614	−.0686	−.1071	.....	.....	.....	.....	.....	.....
1 655 100	30 000	−.1190	−.0690	−.0771	−.1281	−.0159	−.0082	−.0076	−.0118	−.0125	−.0115
[a] 1 853 000	33 600	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
[b] 1 894 000	34 300	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
[c] 1 801 000	32 700	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
[d] 1 848 000	33 500	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
[e] 1 280 000	23 200	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....

Load, pounds	Load in pounds per square inch	11	12	13	14	15	16	17	18	19	20
55 170	1000	0	0	0	0	0	0	0	0	0	0
275 850	5000	+.0006	+.0004	−.0010	−.0007	−.0006	+.0003	+.0004	−.0009	−.0010	−.0011
551 700	10 000	+.0008	+.0012	−.0019	−.0021	−.0018	+.0008	+.0008	−.0019	−.0023	−.0024
827 550	15 000	+.0014	+.0016	−.0038	−.0029	−.0032	+.0012	+.0014	−.0032	−.0035	−.0038
1 103 400	20 000	+.0020	+.0024	−.0052	−.0042	−.0043	+.0018	+.0018	−.0050	−.0050	−.0055
1 379 250	25 000	+.0028	+.0032	−.0070	−.0061	−.0060	+.0021	+.0024	−.0061	−.0063	−.0071
1 655 100	30 000	+.0035	+.0042	−.0088	−.0076	−.0073	+.0028	+.0031	−.0079	−.0079	−.0094

Load, pounds	Load in pounds per square inch	21	22	23	24	25	26	27	28	29	30
55 170	1000	0	0	0	0	0	0	0	0	0	0
275 850	5000	+.0007	+.0002	−.0015	−.0020	−.0019	−.0006	+.0001	.0000	+.0001	+.0007
551 700	10 000	+.0005	+.0006	−.0034	−.0036	.....	.....	.....	.....	.....	.....
827 550	15 000	+.0018	+.0011	−.0050	−.0052	−.0021	−.0014	−.0001	+.0002	.0000	+.0007
1 103 400	20 000	+.0021	+.0016	−.0068	−.0074	.....	.....	.....	.....	.....	.....
1 379 250	25 000	+.0028	+.0023	−.0090	−.0098	−.0019	−.0014	−.0029	+.0014	+.0002	+.0009
1 655 100	30 000	+.0036	+.0028	−.0112	−.0124	.....	.....	.....	.....	.....	.....

Load, pounds	Load in pounds per square inch	31	32	33	34	35	36	37	38	39	40
55 170	1000	0	0	0	0	0	0	0	0	0	0
275 850	5000	+.0001	−.0002	+.0002	+.0001	+.0004	+.0002	+.0002	+.0004	−.0001	−.0001
827 550	15 000	−.0006	−.0005	+.0002	+.0004	+.0006	+.0003	+.0004	+.0002	+.0002	−.0002
1 379 250	25 000	−.0004	−.0006	+.0002	+.0006	+.0007	+.0002	+.0009	+.0003	+.0008	+.0001

Load, pounds	Load in pounds per square inch	41	42	43	44	45	46	47	48
55 170	1000	0	0	0	0	0	0	0	0
275 850	5000	−.0007	.0000	+.0004	+.0003	+.0002	+.0001	−.0001	−.0002
827 550	15 000	−.0012	+.0002	+.0004	+.0004	+.0003	.0000	.0000	.0000
1 379 250	25 000	−.0012	+.0008	−.0002	+.0004	+.0007	.0000	+.0007	+.0008

[a] Slight scaling of steel.
[b] Maximum load.
[c] Load fell off to this value.
[d] Began to show pronounced failure at end (see photograph).
[e] Load fell off to this value.

NOTE.—Stations 1 to 4, inclusive, give compressions in inches in gauge length of 80 inches. Other stations give (±) elongations in a gauge length of 8 inches.

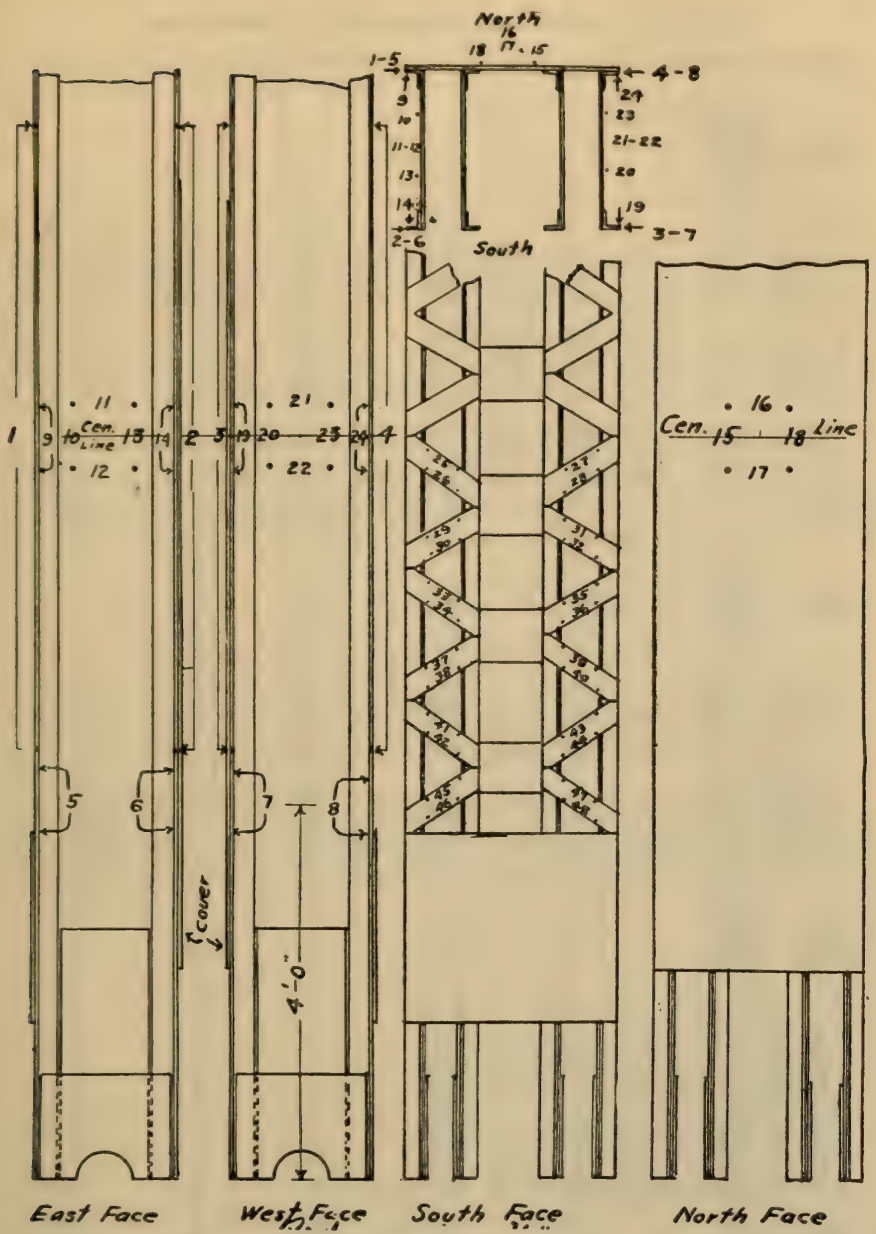


FIG. 16.—*Column US_2MS_1 (carbon steel). Key to stations on Table 16*

TABLE 17.—Log of Test, Column US_2MS_1, Mayari Steel

[Cumulative (±) Elongations at Stations Below. Tested Jan. 22, 1914. Time of Test, 2 p. m. to 4.15 p. m.]

Load, pounds	Load in pounds per square inch	1	2	3	4	5	6	7	8	9	10
42 470	1000	0	0	0	0	0	0	0	0	0	0
212 350	5000	−.0131	−.0105	−.0085	−.0102	−.0004	−.0008	−.0012	−.0007	−.0014	.....
424 700	10 000	−.0297	−.0221	−.0190	−.0263	−.0007	−.0018	−.0026	−.0014	−.0031	−.0026
637 050	15 000	−.0457	−.0304	−.0324	−.0421	−.0012	−.0032	−.0041	−.0022	−.0048	.....
849 400	20 000	−.0628	−.0451	−.0414	−.0594	−.0017	−.0046	−.0057	−.0031	−.0068	−.0059
1 061 750	25 000	−.0801	−.0559	−.0525	−.0765	−.0020	−.0058	−.0072	−.0038	−.0086	.....
1 167 920	27 500	−.0888	−.0618	−.0583	−.0857	.....	.....	.....	.....	.....	.....
1 274 100	30 000	−.0983	−.0678	−.0635	−.0944	−.0022	−.0069	−.0083	−.0048	−.0108	−.0098
1 380 270	32 500	−.1074	−.0730	−.0697	−.1041	.....	.....	.....	.....	.....	.....
1 486 450	35 000	−.1176	−.0784	−.0754	−.1141	−.0028	−.0078	−.0098	−.0061	−.0133	.....
1 592 630	37 500	−.1279	−.0836	−.0806	−.1250	.....	.....	.....	.....	.....	.....
1 698 800	40 000	−.1390	−.0881	−.0865	−.1361	−.0027	−.0096	−.0108	−.0076	−.0219	.....
1 804 970	42 500	−.1520	−.0924	−.0914	−.1487	.....	.....	.....	.....	.....	.....
1 911 150	45 000	−.1686	−.0971	−.0949	−.1670	−.0030	−.0112	−.0114	−.0103	.....	−.0157
[a]2 000 000	47 200	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
[b]1 000 000	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....

Load, pounds	Load in pounds per square inch	11	12	13	14	15	16	17	18	19	20
42 470	1000	0	0	0	0	0	0	0	0	0	0
212 350	5000	.....	.....	.....	−.0012	.....	.....	.....	.....	−.0008	.....
424 700	10 000	+.0009	+.0007	−.0024	−.0025	−.0018	+.0007	+.0007	−.0021	−.0018	−.0024
637 050	15 000	.....	.....	.....	−.0032	.....	.....	.....	.....	−.0032	.....
849 400	20 000	+.0020	+.0019	−.0050	−.0049	−.0040	+.0017	+.0014	−.0043	−.0043	−.0052
1 061 750	25 000	.....	.....	.....	−.0061	.....	.....	.....	.....	−.0056	.....
1 274 100	30 000	+.0025	+.0028	−.0077	−.0073	−.0062	+.0027	+.0024	−.0065	−.0067	−.0080
1 486 450	35 000	.....	.....	.....	−.0085	.....	.....	.....	.....	−.0082	.....
1 698 800	40 000	.....	.....	.....	−.0098	.....	.....	.....	.....	−.0094	.....
1 911 150	45 000	+.0042	+.0048	−.0120	−.0107	−.0088	+.0043	+.0032	−.0091	−.0104	−.0124

Load, pounds	Load in pounds per square inch	21	22	23	24
42 470	1000	0	0	0	0
212 350	5000	.....	.....	.....	−.0014
424 700	10 000	+.0008	+.0009	−.0023	−.0026
637 050	15 000	.....	.....	.....	−.0048
849 400	20 000	+.0016	+.0022	−.0059	−.0066
1 061 750	25 000	.....	.....	.....	−.0084
1 274 100	30 000	+.0026	+.0032	−.0094	−.0104
1 486 450	35 000	.....	.....	.....	−.0123
1 698 800	40 000	.....	.....	.....	−.0147
1 911 150	45 000	+.0044	+.0056	−.0154	−.0173

[a] Maximum load.

[b] Fell off to 1 000 000 pounds. Wrinkles in web and angles west face above pin plates. Same on east face to less extent.

NOTE.—Stations 1, 2, 3, and 4 give compressions in inches in gauge lengths of 80 inches. Other stations give (±) elongations in inches in gauge length of 8 inches.

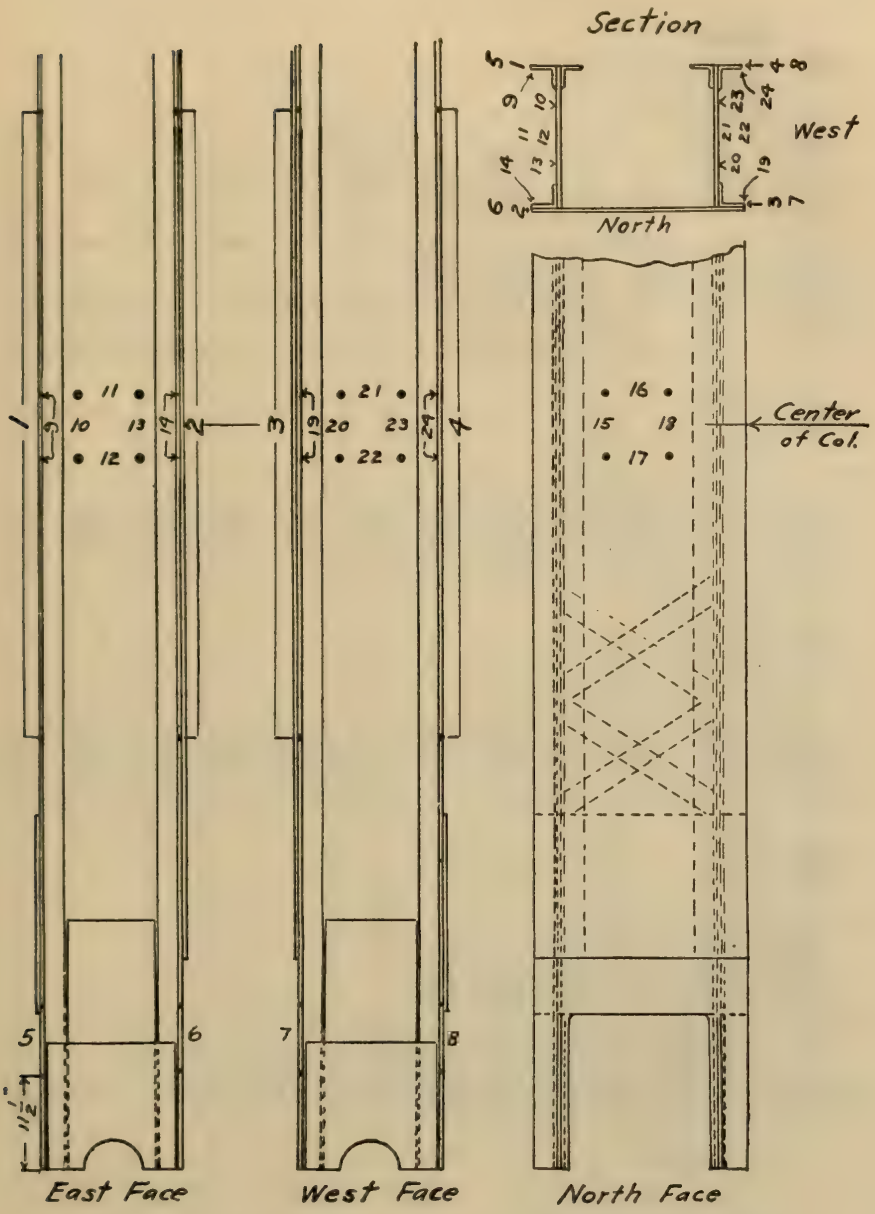


FIG. 17.—*Column US_2MS_1 (Mayari steel). Key to stations on Table 17*

TABLE 18.—Log of Test, Column U_2M_1, Carbon Steel

[Area=96.01. Cumulative (±) Elongations at Stations Below. Tested Jan. 28, 1914.]

Load, pounds	Load in pounds per square inch	1	2	3	4	5	6[a]	7	8	9	10
96 010	1000	0	0	0	0	0	0	0	0	0	0
480 050	5000	−.0140	−.0125	−.0068	−.0074	.....	.....	.....	.....	.....	.....
960 100	10 000	−.0290	−.0281	−.0204	−.0205	−.0029	+.0023	−.0022	−.0028	−.0048	−.0044
1 440 150	15 000	−.0448	−.0444	−.0350	−.0351	.....	.....	.....	.....	.....	.....
1 680 200	17 500	−.0524	−.0533	−.0428	−.0433	.....	.....	.....	.....	.....	.....
1 920 200	20 000	−.0623	−.0635	−.0517	−.0516	−.0067	−.0016	−.0056	−.0063	−.0082	−.0082
2 160 200	22 500	−.0721	−.0745	−.0616	−.0608	.....	.....	.....	.....	.....	.....
2 400 250	25 000	−.0840	−.0874	−.0727	−.0703	.....	.....	.....	.....	.....	.....
2 640 300	27 500	−.0985	−.1040	−.0867	−.0819	.....	.....	.....	.....	.....	.....
2 880 300	30 000	−.1200	−.1311	−.1059	−.0950	−.0192	−.0139	−.0182	−.0130	−.0135	−.0146
[b] 2 980 000	31 000	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....

Load, pounds	Load in pounds per square inch	11	12	13	14	15	16	17[a]	18	19	20
96 010	1000	0	0	0	0	0	0	0	0	0	0
960 100	10 000	+.0013	+.0007	−.0036	−.0036	−.0033	−.0024	−.0024	+.0003	−.0016	−.0020
1 920 200	20 000	+.0023	+.0017	−.0071	−.0071	−.0065	−.0056	−.0016	+.0020	−.0048	−.0048
2 880 300	30 000	+.0045	+.0037	−.0121	−.0126	−.0121	−.0108	+.0003	+.0037	−.0094	−.0091

Load, pounds	Load in pounds per square inch	21	22	23	24	25	26	27	28	29	30
96 010	1000	0	0	0	0	0	0	0	0	0	0
960 100	10 000	−.0025	−.0025	−.0028	−.0029	+.0008	+.0008	+.0008	−.0016	−.0005	−.0007
1 920 200	20 000	−.0060	−.0058	−.0060	−.0066	.....	+.0028	+.0016	−.0031	−.0011	−.0015
2 880 300	30 000	−.0104	−.0106	−.0113	−.0118	+.0032	+.0036	+.0037	−.0046	−.0026	−.0032

Load, pounds	Load in pounds per square inch	31	32	33	34
96 010	1000	0	0	0	0
960 100	10 000	−.0003	+.0009	+.0001	+.0005
1 920 200	20 000	−.0012	+.0015	+.0005	+.0007
2 880 300	30 000	−.0041	+.0015	+.0016	+.0013

[a] Probably the initial gauge reading was in error.
[b] Maximum load. Scaling at 2 960 000 pounds. Sudden failure at lower end.

NOTE.—Stations 1 to 4, inclusive, give compressions in inches in gauge length of 80 inches. Other stations give elongations (±) in inches in gauge length of 8 inches.

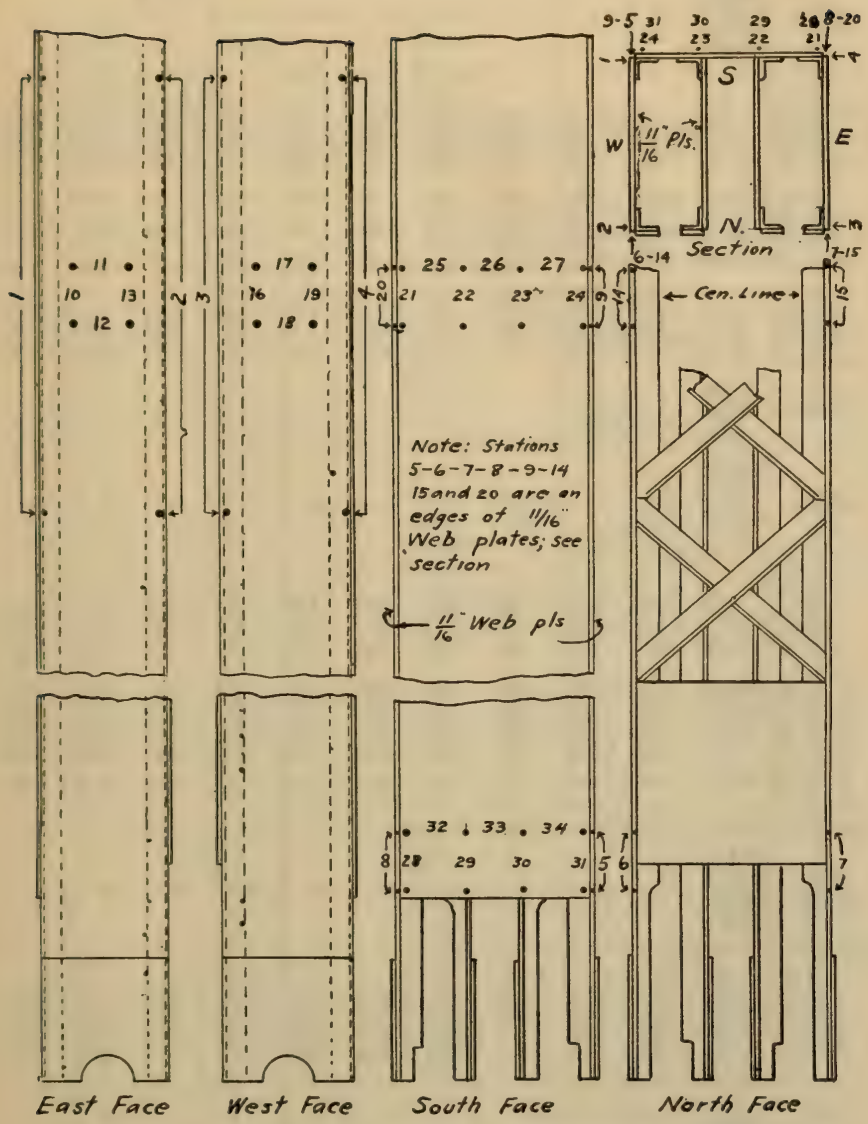


FIG. 18.—*Column $U_2 M_1$ (carbon steel). Key to stations on Table 18*

TABLE 19.—Log of Test, Column U_2M_1, Mayari Steel

[Cumulative (±) Elongations at Stations Below. Tested Jan. 26, 1914. Time of Test, 9.35 a. m. to 12 m.]

Load, pounds	Load in pounds per square inch	1	2	3	4	5	6	7	8	9	10
59 800	900	0	0	0	0	0	0	0	0	0	0
299 000	4490	−.0154	−.0062	−.0041	−.0126	−.0015	−.0013	−.0007	−.0013	−.0016	−.0016
598 000	8990	−.0294	−.0172	−.0140	−.0264	−.0025	−.0025	−.0018	−.0024	−.0031	−.0028
897 000	13 480	−.0437	−.0293	−.0259	−.0403	−.0043	−.0037	−.0028	−.0039	−.0044	−.0042
1 196 000	17 970	−.0576	−.0417	−.0371	−.0532	−.0059	−.0049	−.0042	−.0057	−.0058	−.0057
1 495 000	22 460	−.0719	−.0532	−.0491	−.0663	−.0076	−.0062	−.0054	−.0072	−.0073	−.0070
1 644 500	24 700	−.0797	−.0600	−.0551	−.0742	.....	.....	.....	.....	.....	.....
1 794 000	26 960	−.0870	−.0657	−.0615	−.0812	−.0091	−.0076	−.0066	−.0090	−.0088	−.0085
1 943 500	29 200	−.0951	−.0723	−.0678	−.0887	.....	.....	.....	.....	.....	.....
2 093 000	31 450	−.1034	−.0789	−.0741	−.0960	−.0109	−.0092	−.0079	−.0106	−.0104	−.0100
2 242 500	33 700	−.1119	−.0854	−.0804	−.1040	.....	.....	.....	.....	.....	.....
2 392 000	35 940	−.1205	−.0923	−.0868	−.1122	−.0124	−.0109	−.0093	−.0126	−.0126	−.0118
2 691 000	40 430	−.1400	−.1057	−.1000	−.1301	−.0151	−.0125	−.0104	−.0145	−.0157	−.0132
2 990 000	44 930	−.1619	−.1206	−.1135	−.1500	−.0184	−.0146	−.0116	−.0169	−.0196	−.0155
[a] 3 289 000	49 420	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
[b] 3 103 500	46 600	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
[c] 200 000	3010	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....

Load, pounds	Load in pounds per square inch	11	12	13	14	19	20	21	22	23	24
59 800	900	0	0	0	0	0	0	0	0	0	0
299 000	4490	+.0003	+.0006	−.0010	−.0006	−.0004	−.0008	+.0004	+.0003	−.0011	−.0015
598 000	8990	+.0007	+.0009	−.0022	−.0019	−.0016	−.0019	+.0008	+.0009	−.0023	−.0027
897 000	13 480	+.0011	+.0012	−.0035	−.0028	−.0028	−.0030	+.0012	+.0013	−.0037	−.0042
1 196 000	17 970	+.0013	+.0014	−.0048	−.0040	−.0040	−.0042	+.0015	+.0014	−.0051	−.0057
1 495 000	22 460	+.0017	+.0019	−.0063	−.0054	−.0052	−.0056	+.0019	+.0016	−.0061	−.0071
1 794 000	26 960	+.0021	+.0022	−.0076	−.0066	−.0065	−.0068	+.0024	+.0023	−.0075	−.0085
2 093 000	31 450	+.0025	+.0026	−.0090	−.0079	−.0078	−.0080	+.0028	+.0027	−.0089	−.0102
2 392 000	35 940	+.0029	+.0031	−.0105	−.0093	−.0092	−.0094	+.0032	+.0031	−.0105	−.0123
2 691 000	40 430	+.0031	+.0035	−.0121	−.0106	−.0103	−.0108	+.0038	+.0036	−.0122	−.0148
2 990 000	44 930	+.0033	+.0040	−.0137	−.0119	−.0114	−.0122	+.0043	+.0039	−.0139	−.0183
3 289 000	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....

Load, pounds	Load in pounds per square inch	25	26	27	28	29	30	31	32	33	34
59 800	900	0	0	0	0	0	0	0	0	0	0
598 000	8990	−.0006	−.0008	−.0012	−.0017	−.0012	−.0008	−.0004	−.0002	−.0001	−.0007
1 196 000	17 970	−.0014	−.0017	−.0025	−.0031	−.0030	−.0018	−.0010	−.0006	−.0005	−.0016
1 794 000	26 960	−.0023	−.0027	−.0030	−.0042	−.0040	−.0028	−.0014	−.0009	−.0008	−.0030
2 392 000	35 940	−.0030	−.0031	−.0043	−.0053	−.0051	−.0035	−.0022	−.0016	−.0016	−.0045
2 990 000	44 930	−.0040	−.0041	−.0050	−.0059	−.0056	−.0042	−.0033	−.0028	−.0036	−.0078

Load, pounds	Load in pounds per square inch	35	36	37	38	39	40	41	42	43	44
59 800	900	0	0	0	0	0	0	0	0	0	0
598 000	8990	.....	−.0034	−.0025	−.0007	−.0004	−.0006	+.0003	+.0004	+.0006	+.0004
1 196 000	17 970	−.0019	−.0076	−.0055	−.0017	−.0010	−.0006	+.0006	+.0006	+.0010	+.0010
1 794 000	26 960	−.0046	−.0112	−.0084	−.0031	−.0016	−.0003	+.0008	+.0008	+.0017	+.0015
2 392 000	35 940	−.0075	−.0156	−.0127	−.0054	−.0028	−.0006	+.0010	+.0010	+.0024	+.0022
2 990 000	44 930	−.0132	−.0274	−.0215	−.0101	−.0054	−.0021	+.0012	+.0010	+.0032	+.0030

[a] Maximum load. [b] Sudden failure at lower end. [c] Final reading after load fell off.

TABLE 19.—Log of Test, Column U_2M_1, Mayari Steel—Continued

Load, pounds	Load in pounds per square inch	45	46	47	48
59 800	900	0	0	0	0
598 000	8990	−.0004	−.0003	−.0003	+.0008
1 196 000	17 970	−.0004	−.0002	−.0009	+.0016
1 794 000	26 960	0	+.0007	−.0003	+.0026
2 392 000	35 940	+.0010	+.0032	−.0011	+.0035
2 990 000	44 930	+.0047	+.0122	+.0061	+.0042

NOTE.—Stations 1 to 4, inclusive, give compression in inches in gauge length of 80 inches. Other stations give elongation (±) in inches in gauge length of 8 inches.

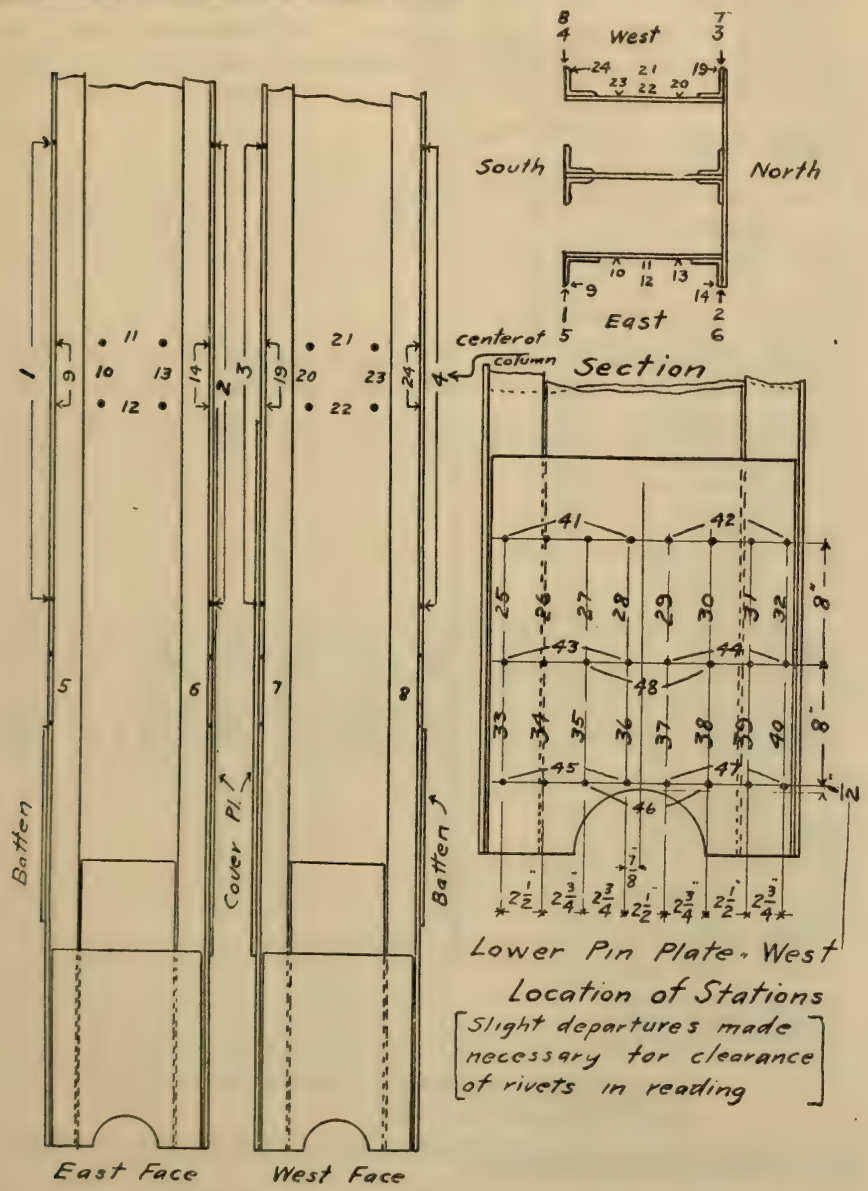


FIG. 29.—*Column U_2M_1 (Mayari steel). Key to stations on Table 19*

TABLE 20.—Log of Test, Column LC_0LC_1, Carbon Steel

[Cumulative (±) Elongations at Stations Below. Tested Jan. 28, 1914. Time of Test, 9.32 a. m. to 12 m.]

Load, pounds	Load in pounds per square inch	1	2	3	4	5	6	7	8	9	10
119 000	1000	0	0	0	0	0	0	0	0	0	0
595 000	5000	−.0128	−.0082	−.0097	−.0122	−.0012	−.0013	−.0008	−.0014	−.0015	−.0014
1 190 000	10 000	−.0271	−.0217	−.0238	−.0267	−.0028	−.0031	−.0027	−.0031	−.0033	.....
1 785 000	15 000	−.0420	−.0367	−.0388	−.0422	−.0047	−.0049	−.0044	−.0046	−.0051	−.0047
2 082 500	17 500	−.0510	−.0446	−.0475	−.0510	.....	.....	.....	.....	.....	.....
2 380 000	20 000	−.0600	−.0543	−.0566	−.0600	−.0071	−.0075	−.0068	−.0068	−.0079	.....
2 677 500	22 500	−.0714	−.0648	−.0680	−.0720	.....	.....	.....	.....	.....	.....
2 975 000	25 000	−.0859	−.0779	−.0827	−.0880	−.0104	−.0117	−.0106	−.0106	−.0120	−.0105
3 272 500	27 500	−.1029	−.0951	−.1034	−.1090	.....	.....	.....	.....	.....	.....
3 570 000	30 000	−.1248	−.1201	−.1390	−.1454	−.0170	−.0195	−.0216	.....	−.0204	.....
[a] 3 820 000	32 100	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
[b] 3 858 000	32 400	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
[c] 2 100 000	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....

Load, pounds	Load in pounds per square inch	11	12	13	14	15	16	17	18	19	20
119 000	1000	0	0	0	0	0	0	0	0	0	0
595 000	5000	+.0005	+.0003	−.0008	−.0010	−.0010	−.0009	−.0009	−.0008	−.0007	−.0010
1 190 000	10 000	.....	.....	.....	−.0025	−.0024	−.0025	−.0020	−.0024	−.0022	.....
1 785 000	15 000	+.0015	+.0013	−.0041	−.0039	−.0040	−.0040	−.0036	−.0040	−.0037	−.0036
2 380 000	20 000	.....	.....	.....	−.0057	−.0059	−.0061	−.0050	−.0057	−.0055	.....
2 975 000	25 000	+.0029	+.0028	−.0095	−.0081	−.0084	−.0085	−.0070	−.0084	−.0085	−.0085
3 570 000	30 000	.....	.....	.....	−.0135	−.0130	−.0124	−.0120	−.0140	−.0114	.....

Load, pounds	Load in pounds per square inch	21	22	23	24	25	26	27	28	29	30
119 000	1000	0	0	0	0	0	0	0	0	0	0
595 000	5000	+.0003	+.0004	−.0011	−.0015	−.0012	−.0012	−.0012	−.0011	.0000	+.0001
1 190 000	10 000	.....	.....	.....	−.0030	−.0027	−.0027	−.0027	−.0026	.....	.....
1 785 000	15 000	+.0013	+.0013	−.0040	−.0046	−.0044	−.0046	−.0044	−.0042	+.0003	+.0001
2 380 000	20 000	.....	.....	.....	−.0063	−.0063	−.0074	−.0067	−.0062	.....	.....
2 975 000	25 000	+.0030	+.0027	−.0091	−.0080	−.0094	−.0109	−.0105	−.0093	+.0007	+.0004
3 570 000	30 000	.....	.....	.....	−.0087	−.0149	−.0146	−.0184	−.0146	+.0008	+.0006

Load, pounds	Load in pounds per square inch	31
119 000	1000	0
595 000	5000	−.0001
1 190 000	10 000	.....
1 785 000	15 000	−.0003
2 380 000	20 000	.....
2 975 000	25 000	−.0004
3 570 000	30 000	−.0007

[a] Failure commenced. First deflection. Buckled east 4 inches.
[b] Maximum load. Held for several minutes.
[c] Load fell off gradually to this value.

NOTE.—Stations 1 to 4, inclusive, give compressions in inches in gauge length of 80 inches. Other stations give (±) elongations in a gauge length of 8 inches.

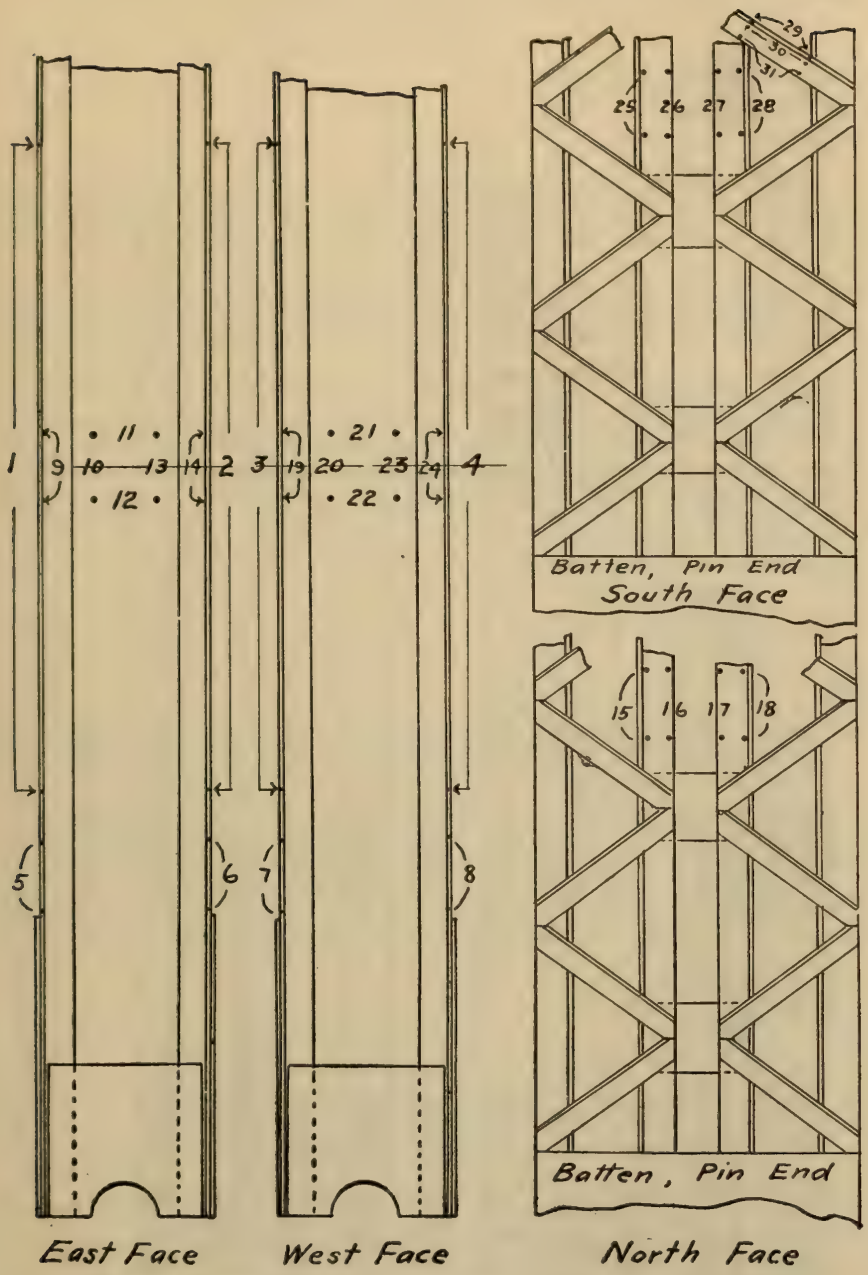


FIG. 20.—*Column LC_0 LC_1 (carbon steel). Key to stations on Table 20*

TABLE 21.—Log of Test, Column LC_0LC_1, Mayari Steel

[Area=75.1. Cumulative (±) Elongations at Stations Below. Tested Jan. 23, 1914. Time of test, 1.30 p. m. to 4.15 p. m.]

Load, pounds	Load in pounds per square inch	1	2	3	4	5	6	7	8	9	10
75 100	1000	0	0	0	0	0	0	0	0	0	0
375 600	5000	−.0120	−.0083	−.0084	−.0116	−.0020	−.0013	−.0008	−.0010	−.0014	−.0014
751 300	10 000	−.0259	−.0217	−.0200	−.0248	−.0037	−.0027	−.0027	−.0028	−.0029	−.0030
1 126 900	15 000	−.0396	−.0349	−.0328	−.0377	−.0053	−.0041	−.0042	.....	−.0044	.....
1 502 500	20 000	−.0537	−.0483	−.0457	−.0509	−.0070	−.0055	−.0060	−.0054	−.0058	−.0058
1 878 100	25 000	−.0676	−.0618	−.0590	−.0635	−.0082	−.0075	−.0079	−.0074	−.0072	.....
2 066 000	27 500	−.0749	−.0690	−.0655	−.0707	.....	.....	.....	.....	.....	.....
2 253 800	30 000	−.0820	−.0754	−.0723	−.0771	−.0105	−.0093	−.0097	−.0090	−.0085	−.0088
2 441 600	32 500	−.0887	−.0830	−.0793	−.0843	.....	.....	.....	.....	.....	.....
2 629 400	35 000	−.0961	−.0900	−.0862	−.0915	−.0125	−.0111	−.0115	−.0109	−.0098	.....
2 817 200	37 500	−.1034	−.0973	−.0941	−.0998	.....	.....	.....	.....	.....	.....
3 005 000	40 000	−.1109	−.1045	−.1014	−.1072	.....	−.0125	−.0137	−.0130	−.0112	−.0116
3 192 800	42 500	−.1189	−.1120	−.1093	−.1152	.....	.....	.....	.....	.....	.....
3 380 600	45 000	−.1269	−.1200	−.1171	−.1240	−.0169	−.0148	−.0164	−.0148	−.0126	.....
3 568 400	47 500	−.1360	−.1287	−.1257	−.1335	.....	.....	.....	.....	.....	.....
3 756 200	50 000	−.1465	−.1380	−.1339	−.1431	−.0205	−.0169	−.0199	−.0178	−.0140	−.0153
4 131 800	55 000	−.1740	−.1610	−.1550	−.1678	.....	−.0207	−.0257	.....	.....	.....
[a] 4 443 000	57 700	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
[b] 3 720 000	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
[c] 2 900 000	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....

Load, pounds	Load in pounds per square inch	11	12	13	14	15	16	17	18	19	20
75 100	1000	0	0	0	0	0	0	0	0	0	0
375 600	5000	+.0004	+.0004	−.0011	−.0009	−.0012	−.0011	−.0007	−.0011	−.0008	−.0015
751 300	10 000	+.0010	+.0014	−.0026	−.0022	−.0027	−.0022	−.0022	−.0024	−.0019	−.0032
1 126 900	15 000	.....	.....	.....	−.0037	−.0041	−.0036	−.0035	−.0037	−.0032	.....
1 502 500	20 000	+.0018	+.0026	−.0056	−.0051	−.0054	−.0050	−.0050	−.0052	−.0050	−.0053
1 878 100	25 000	.....	.....	.....	−.0065	−.0068	−.0064	−.0071	−.0066	−.0062	.....
2 253 800	30 000	+.0028	+.0035	−.0084	−.0079	−.0083	−.0081	−.0079	−.0080	−.0078	−.0065
2 629 400	35 000	.....	.....	.....	−.0093	−.0098	−.0098	−.0095	−.0088	−.0092	.....
3 005 000	40 000	+.0038	+.0046	−.0116	−.0108	−.0110	−.0113	−.0111	−.0104	−.0103	−.0117
3 380 600	45 000	.....	.....	.....	−.0125	−.0122	−.0130	−.0125	−.0121	−.0122	.....
3 756 200	50 000	+.0054	+.0058	−.0149	−.0154	−.0142	−.0145	−.0140	−.0147	−.0138	−.0149
4 131 800	55 000	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....

Load, pounds	Load in pounds per square inch	21	22	23	24	25	26	27	28
75 100	1000	0	0	0	0	0	0	0	0
375 600	5000	+.0005	0	−.0006	−.0013	−.0013	−.0012	−.0012	−.0014
751 300	10 000	+.0007	+.0009	−.0025	−.0026	−.0029	−.0026	−.0023	−.0026
1 126 900	15 000	.....	.....	.....	−.0040	−.0042	−.0038	−.0038	−.0040
1 502 500	20 000	+.0015	+.0017	−.0051	−.0054	−.0053	−.0056	−.0052	−.0054
1 878 100	25 000	.....	.....	.....	−.0069	−.0070	−.0073	−.0068	−.0068
2 253 800	30 000	+.0025	+.0028	−.0079	−.0082	−.0084	−.0088	−.0084	−.0083
2 629 400	35 000	.....	.....	.....	−.0098	−.0100	−.0104	−.0096	−.0101
3 005 000	40 000	+.0034	+.0038	−.0091	−.0115	−.0114	−.0125	−.0108	−.0116
3 380 600	45 000	.....	.....	.....	−.0134	−.0134	−.0142	−.0118	−.0132
3 756 200	50 000	+.0046	+.0051	−.0145	−.0153	−.0154	−.0155	−.0126	−.0152
4 131 800	55 000	.....	.....	.....	.....	.....	.....	.....	.....

[a] Maximum load. Southwest angle had a slight initial dent or wrinkle at center of column which did not seem to appreciably affect strength. Reports were heard at 3 100 000, 3 460 000, and 3 850 000. Slight scaling at 3 930 000.

[b] Wrinkling.

[c] Pronounced wrinkling.

NOTE.—Stations 1 to 4, inclusive, give compression in inches in gauge length of 80 inches. Other stations give elongations (±) in inches in gauge length of 8 inches.

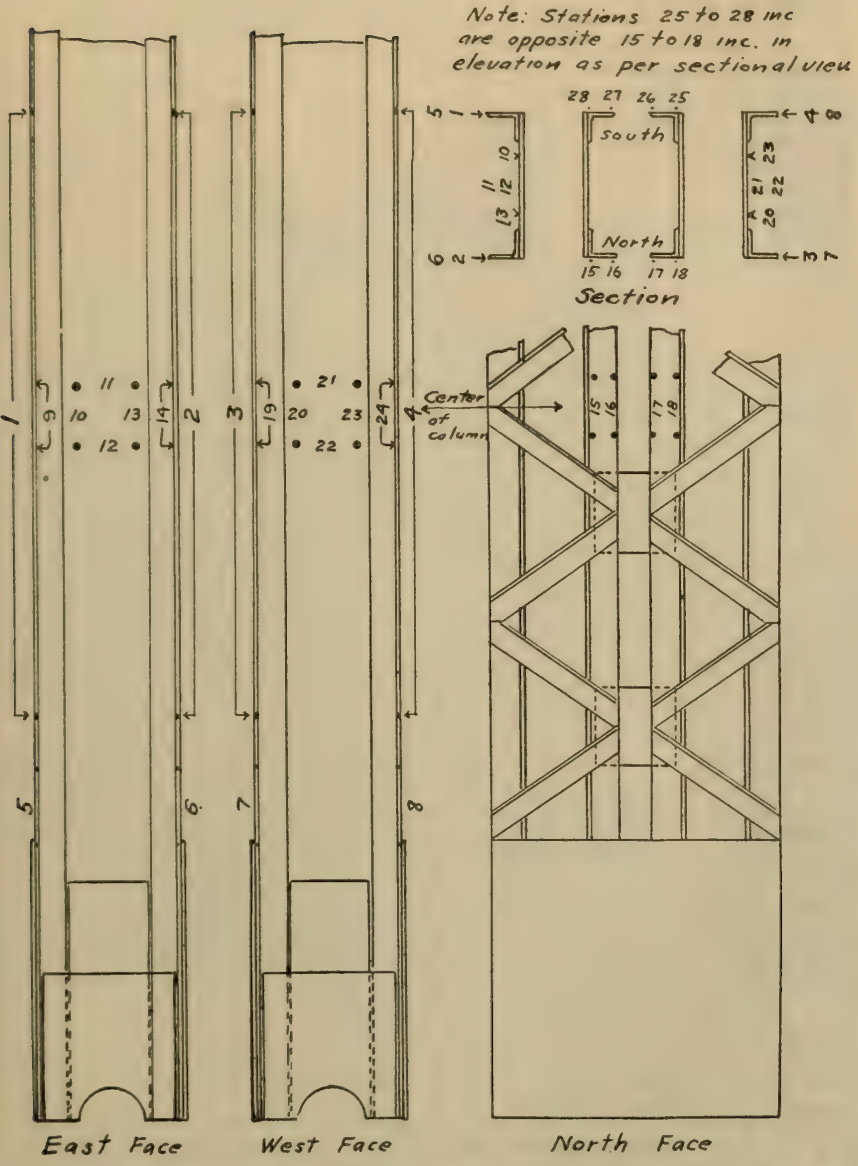


FIG. 21.—*Column LC_0 LC_1 (Mayari steel). Key to stations on Table 21*

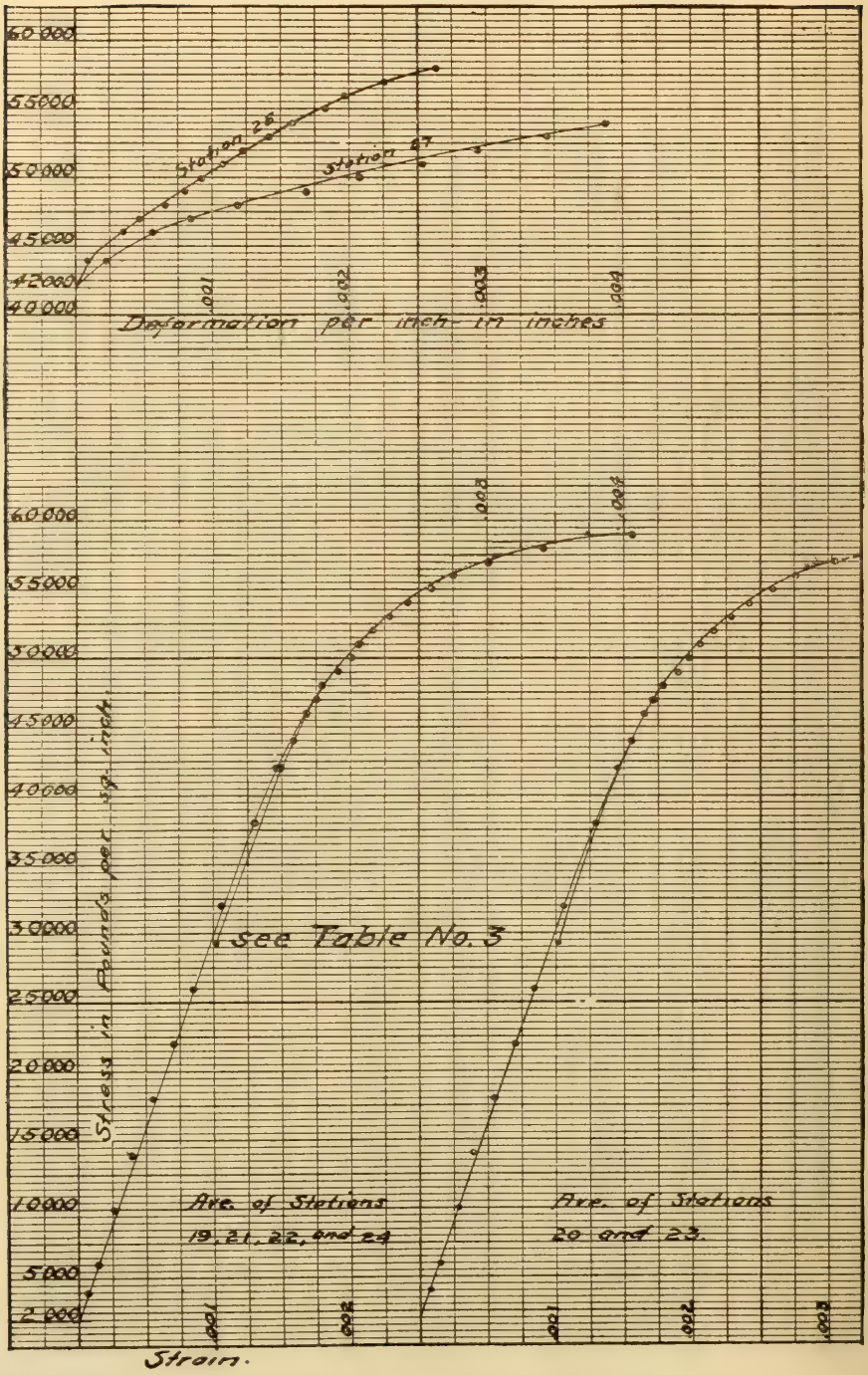


FIG. 22.—*Column U_2U_3 (nickel steel)*

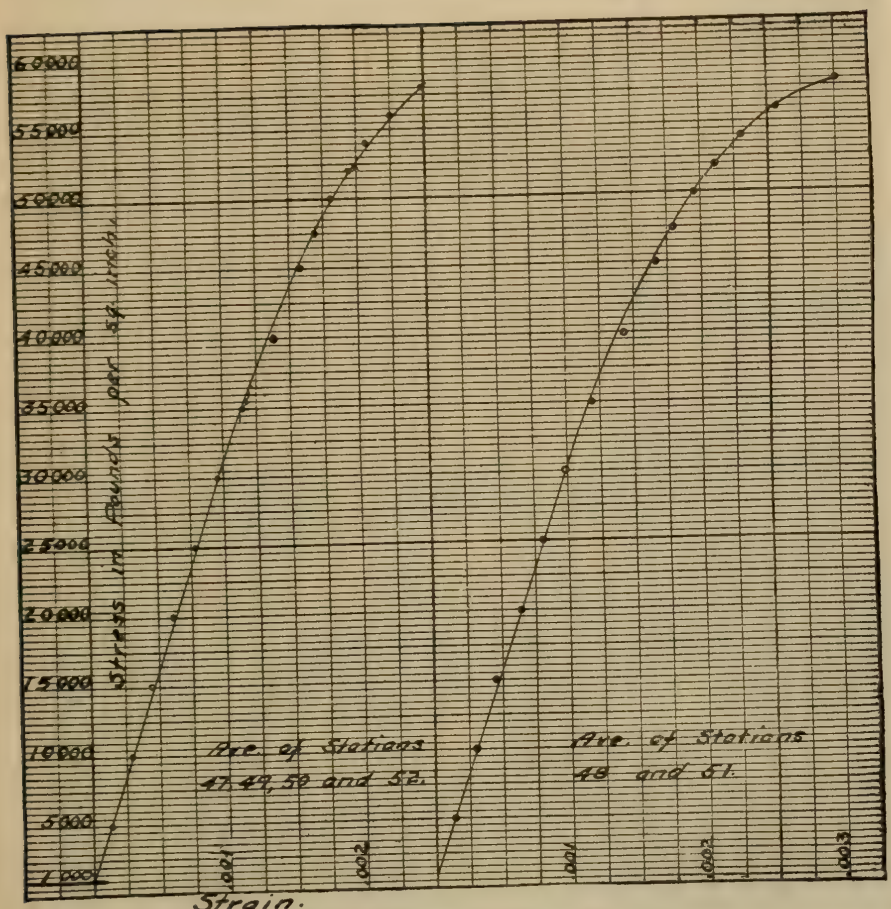


FIG. 23.—*Column U_8U_9 (nickel steel)*

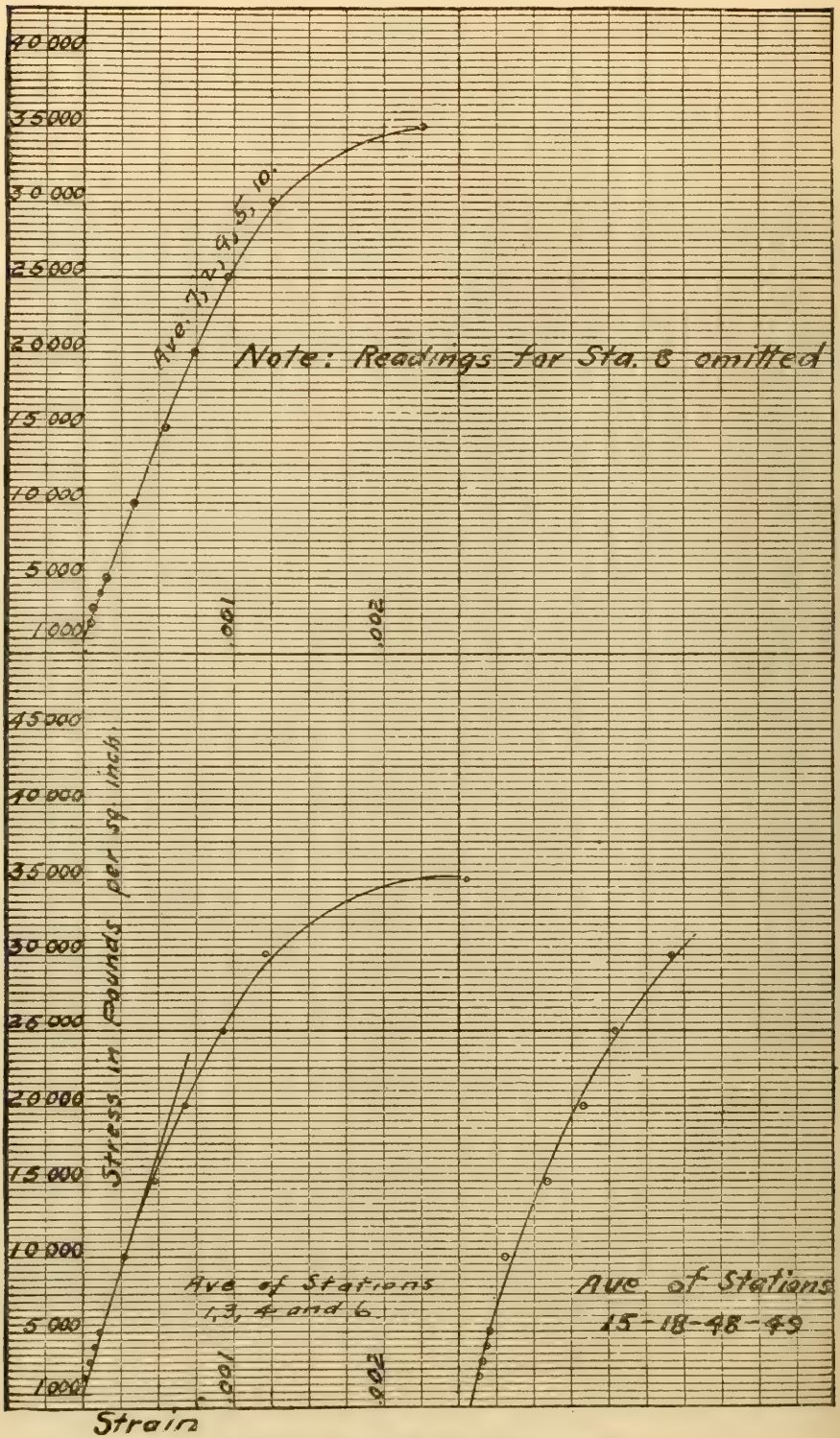


FIG. 24.—*Column HC (high carbon steel)*

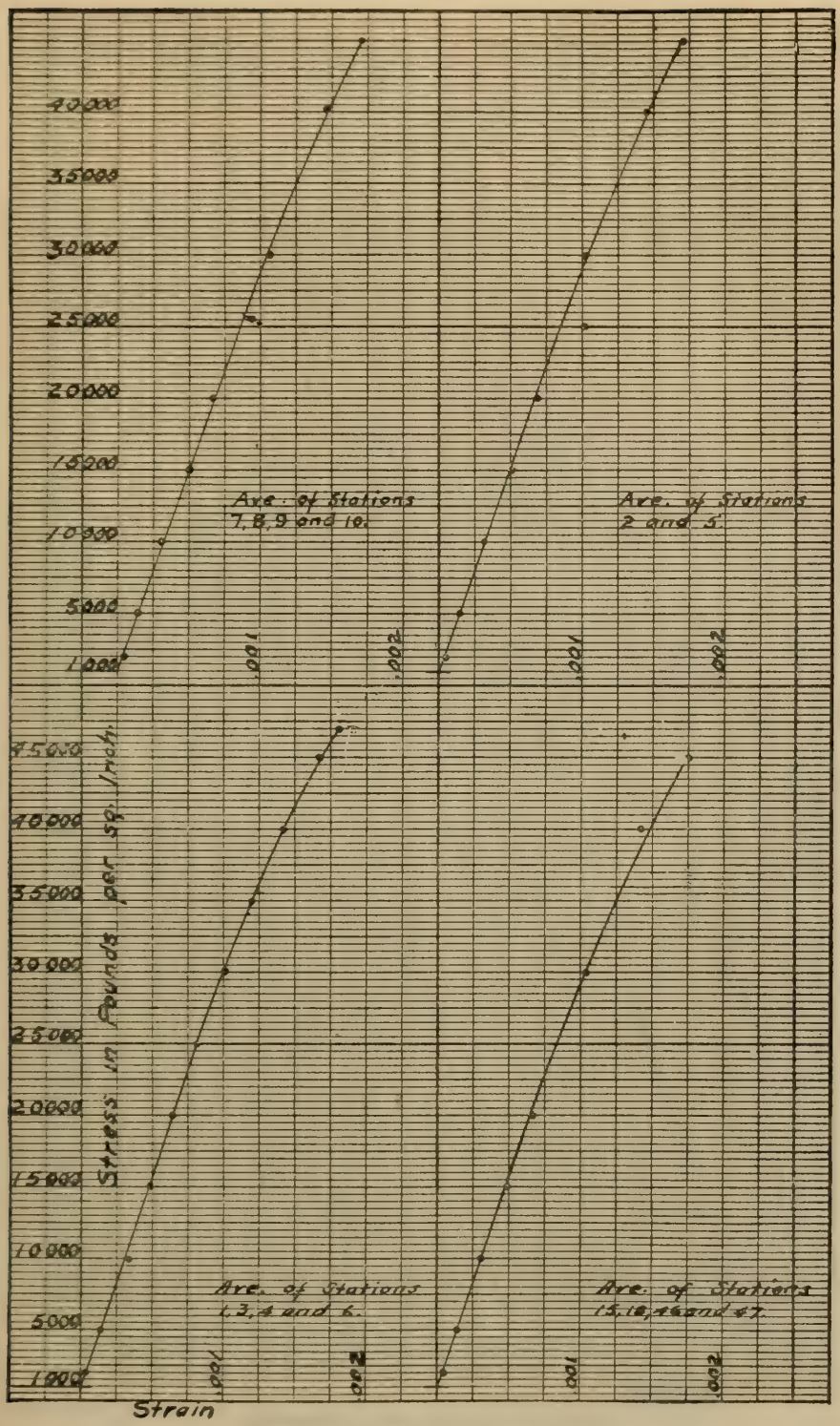


FIG. 25.—*Column MY (Mayari steel)*

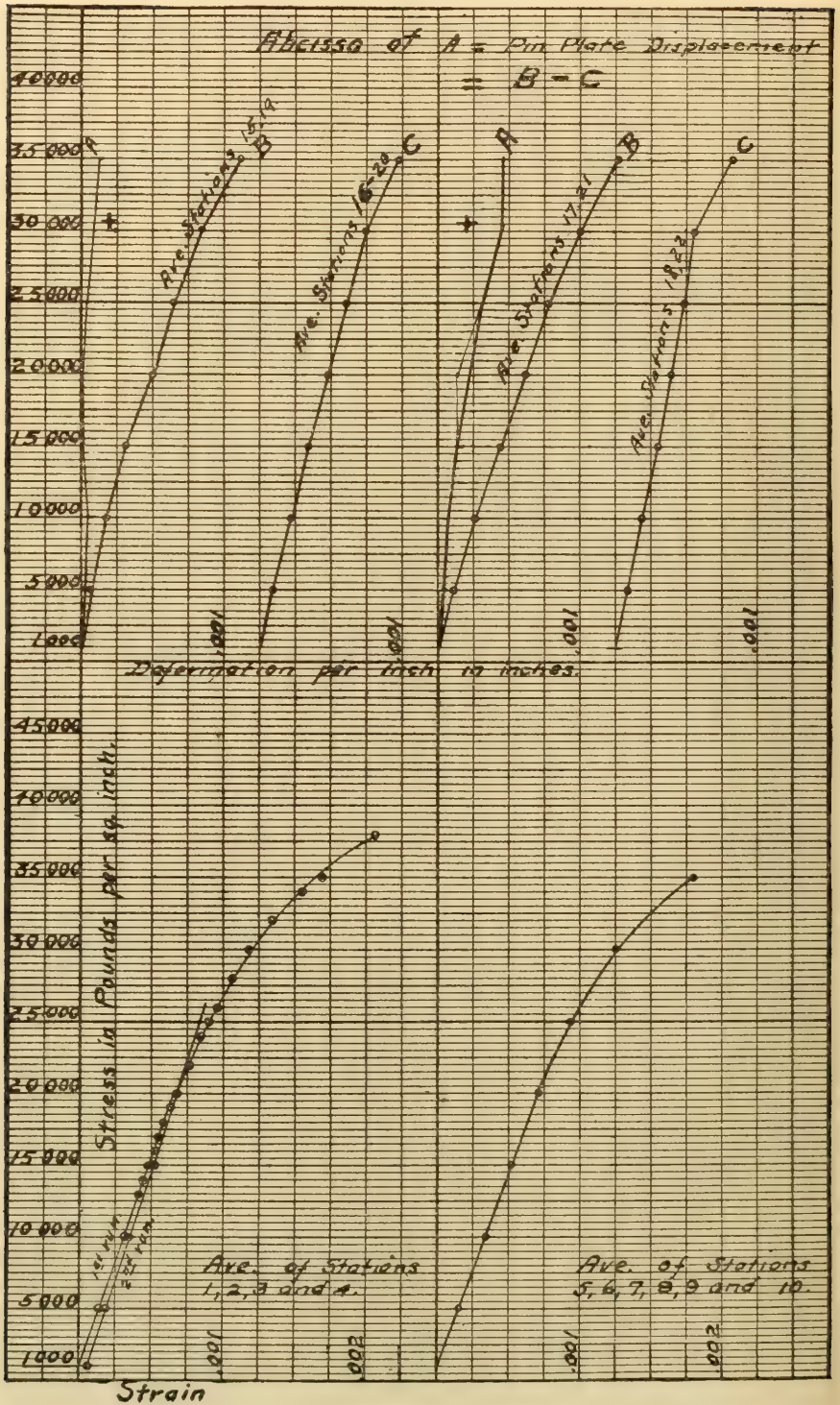

Abscissa of A = Pin Plate Displacement = B - C
Ave. Stations 1, 2, 3 and 4
Ave. Stations 5, 6, 7, 8, 9 and 10
Deformation per inch in inches.
Stress in Pounds per sq. inch.
Strain
Ave. of Stations 1, 2, 3 and 4.
Ave. of Stations 5, 6, 7, 8, 9 and 10.

FIG. 26.—*Column 31HC (carbon steel)*

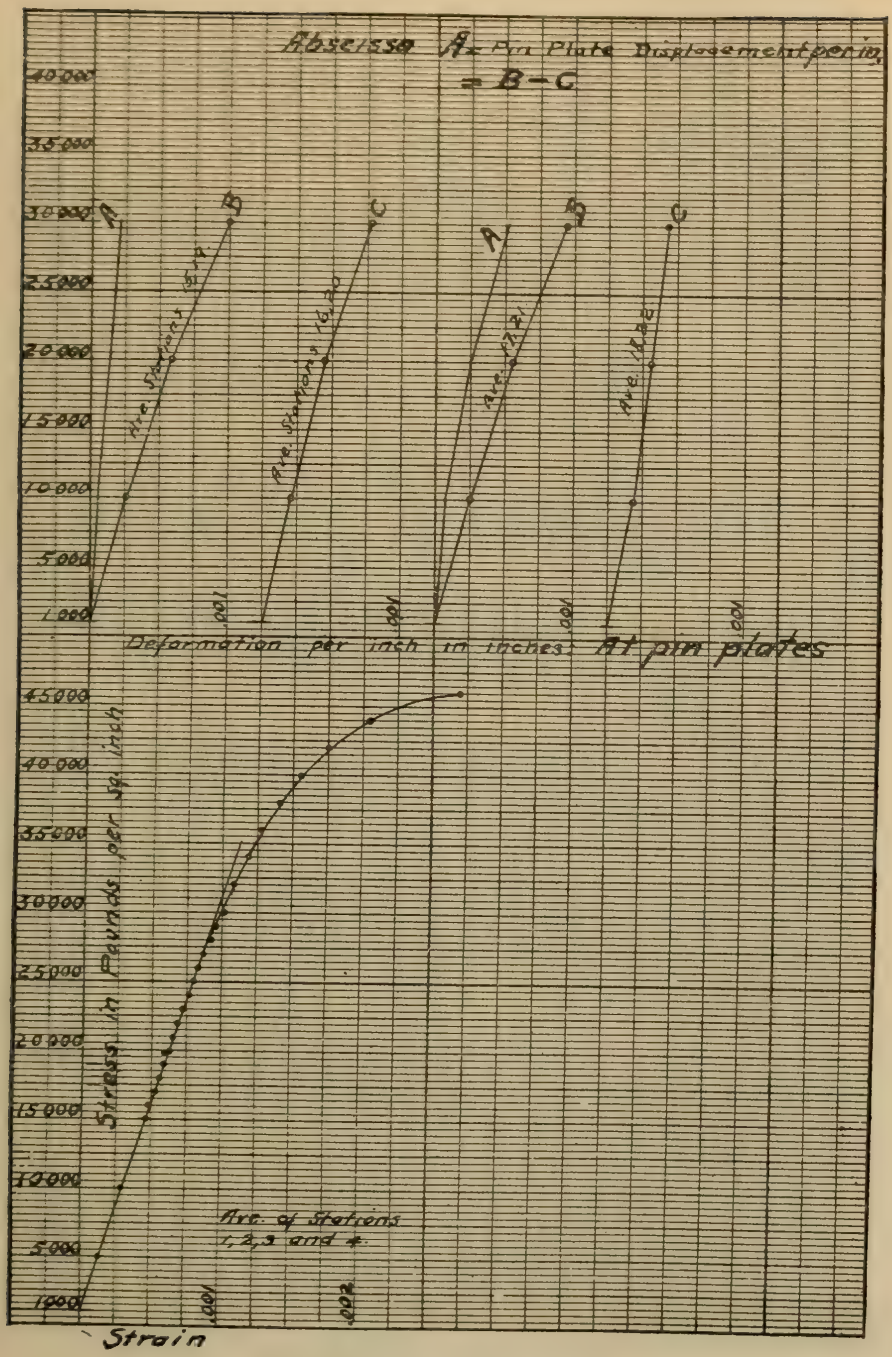

Abscissa A = Pin Plate Displacement per in.
= B − C
Ave. Stations 1 & 4
Ave. Stations 2 & 3
Ave. Load
Deformation per inch in inches at pin plates
Stress in Pounds per Sq. Inch
Ave. of Stations 1, 2, 3 and 4
Strain

FIG. 27.—*Column 32S (silicon steel)*

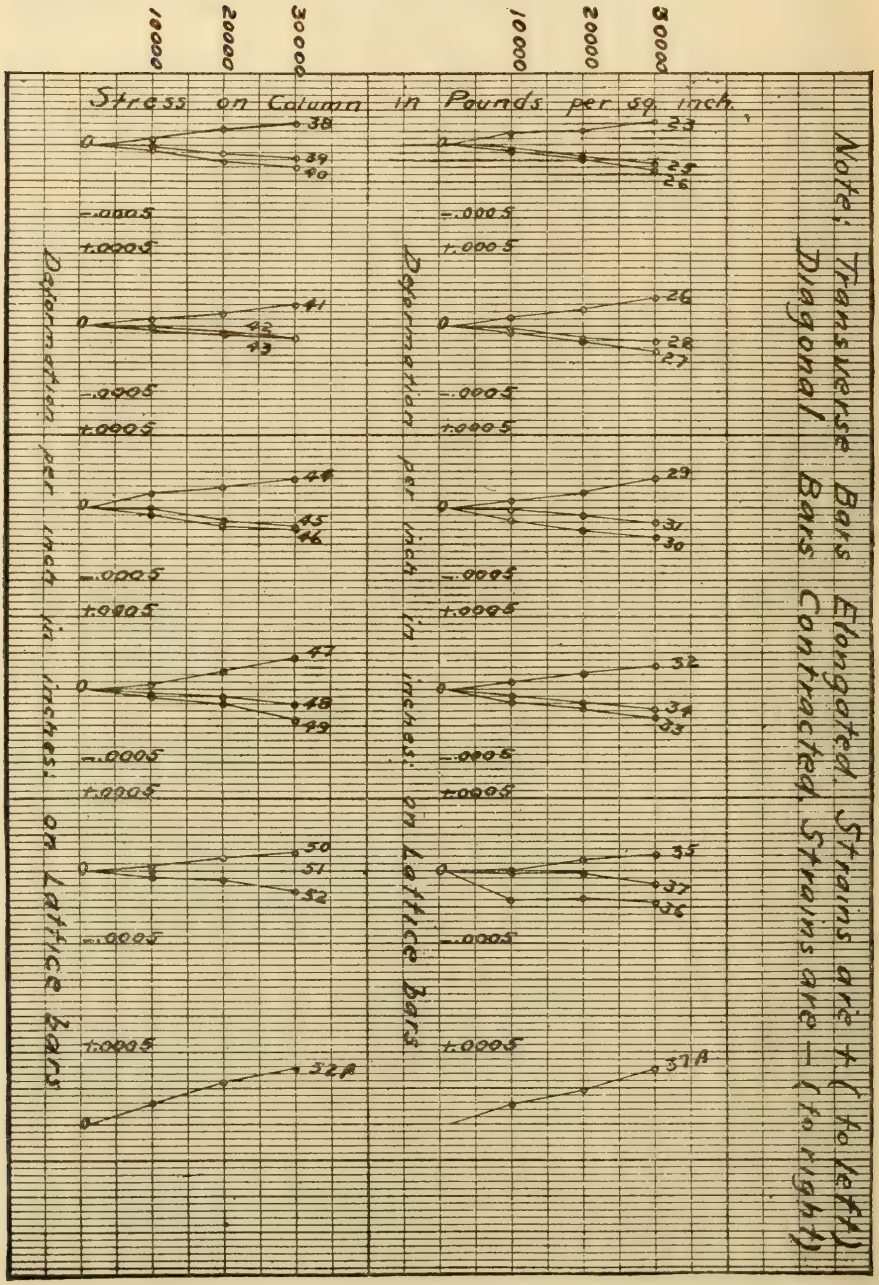


FIG. 28.—*Column 32S (silicon steel)*

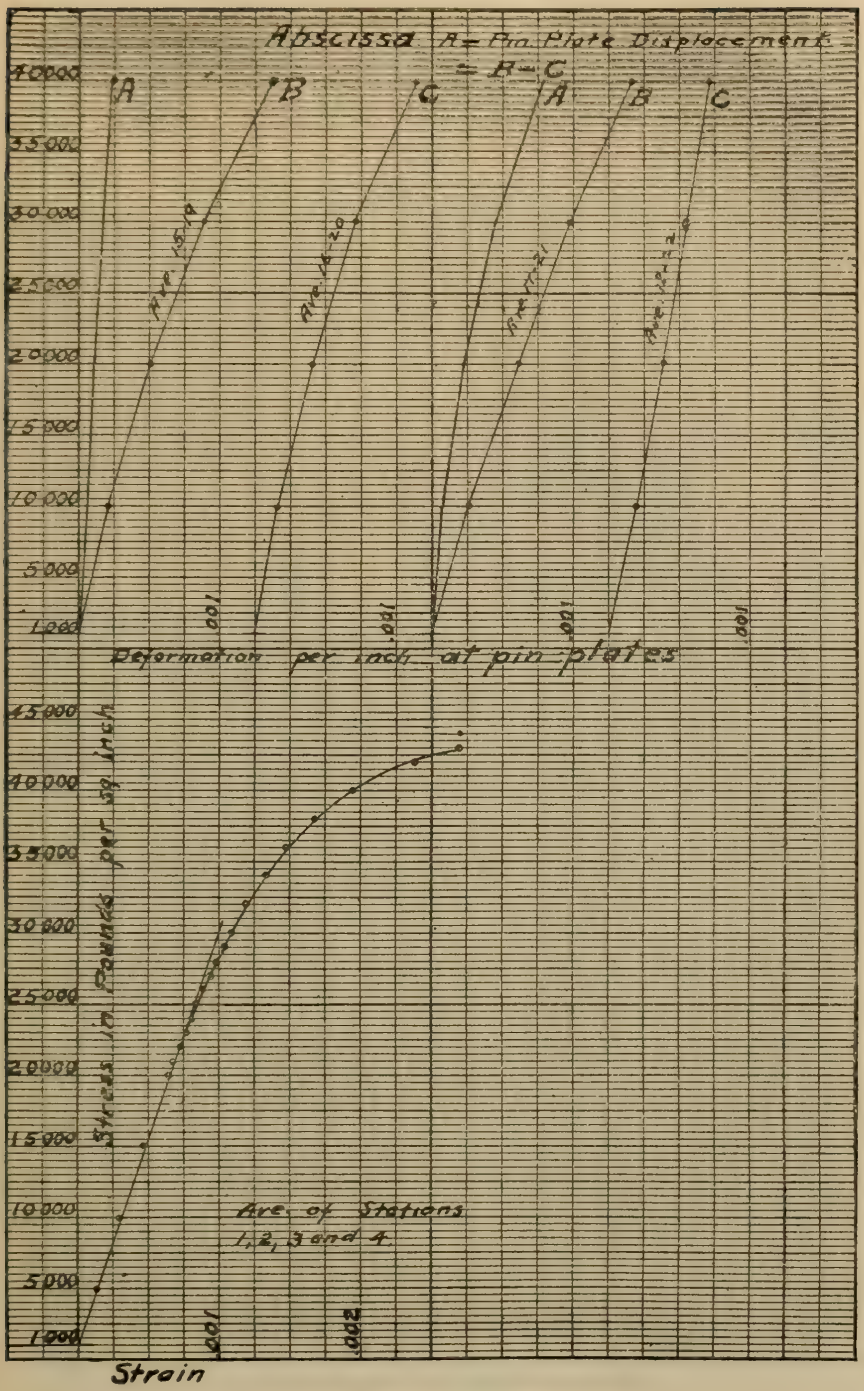


FIG. 29.—*Column 34CS (chrome steel)*

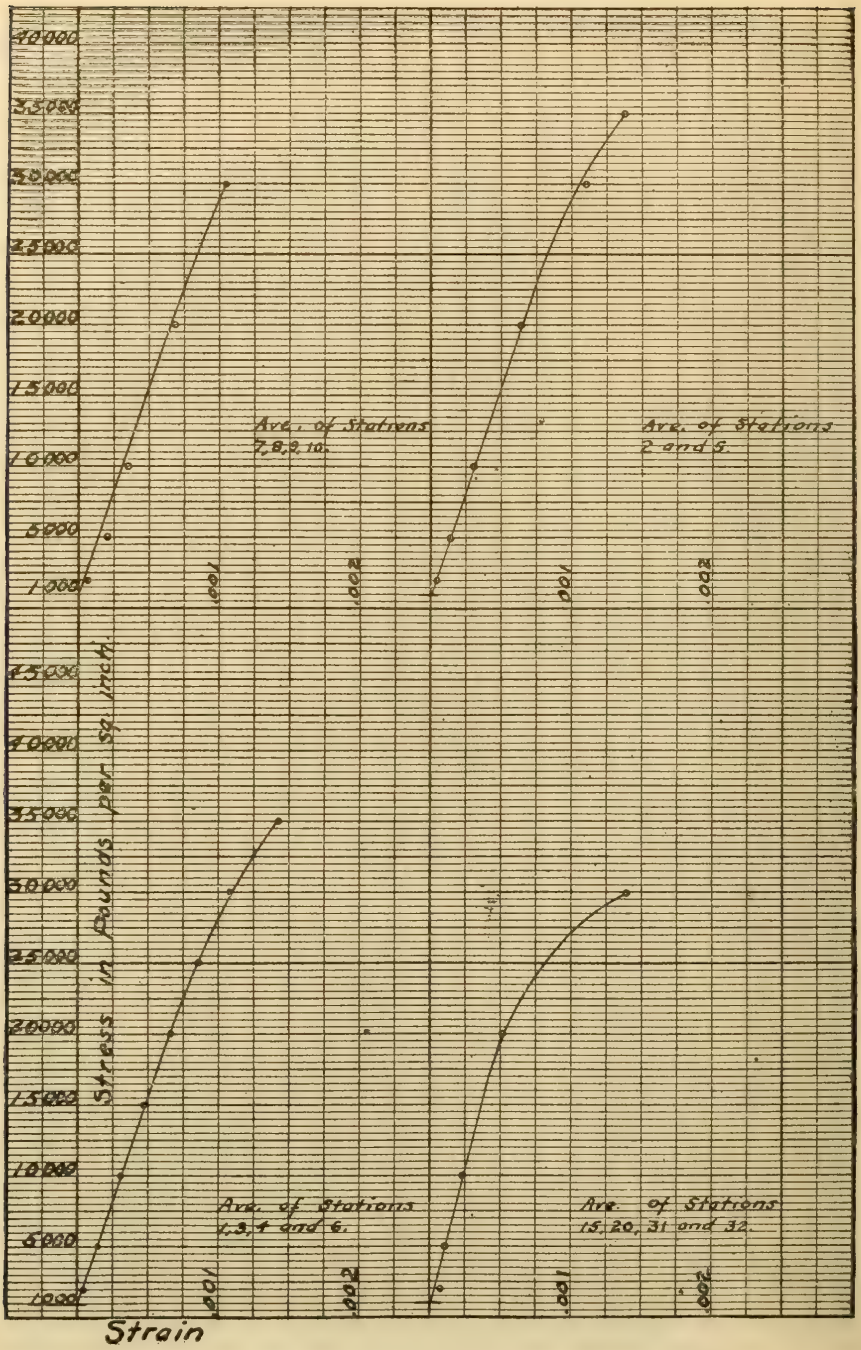

Ave. of Stations 7, 8, 9, 10.
Ave. of Stations 2 and 5.
Ave. of Stations 1, 3, 4 and 6.
Ave. of Stations 15, 20, 31 and 32.
Stress in Pounds per sq. inch.
Strain
.001
.002

FIG. 30.—*Column HC1 (high carbon steel)*

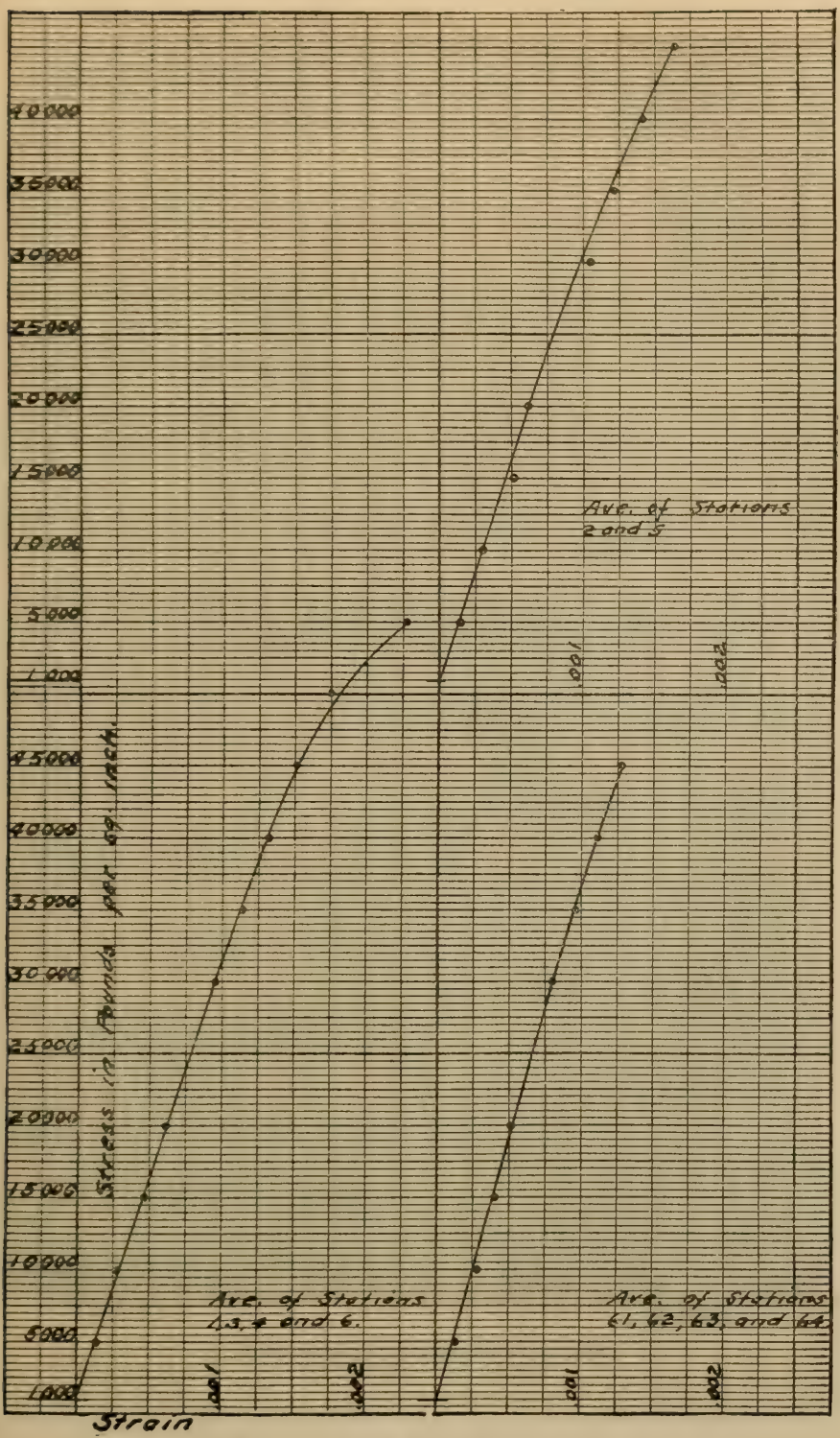


FIG. 31.—*Column MY1 (Mayari steel)*

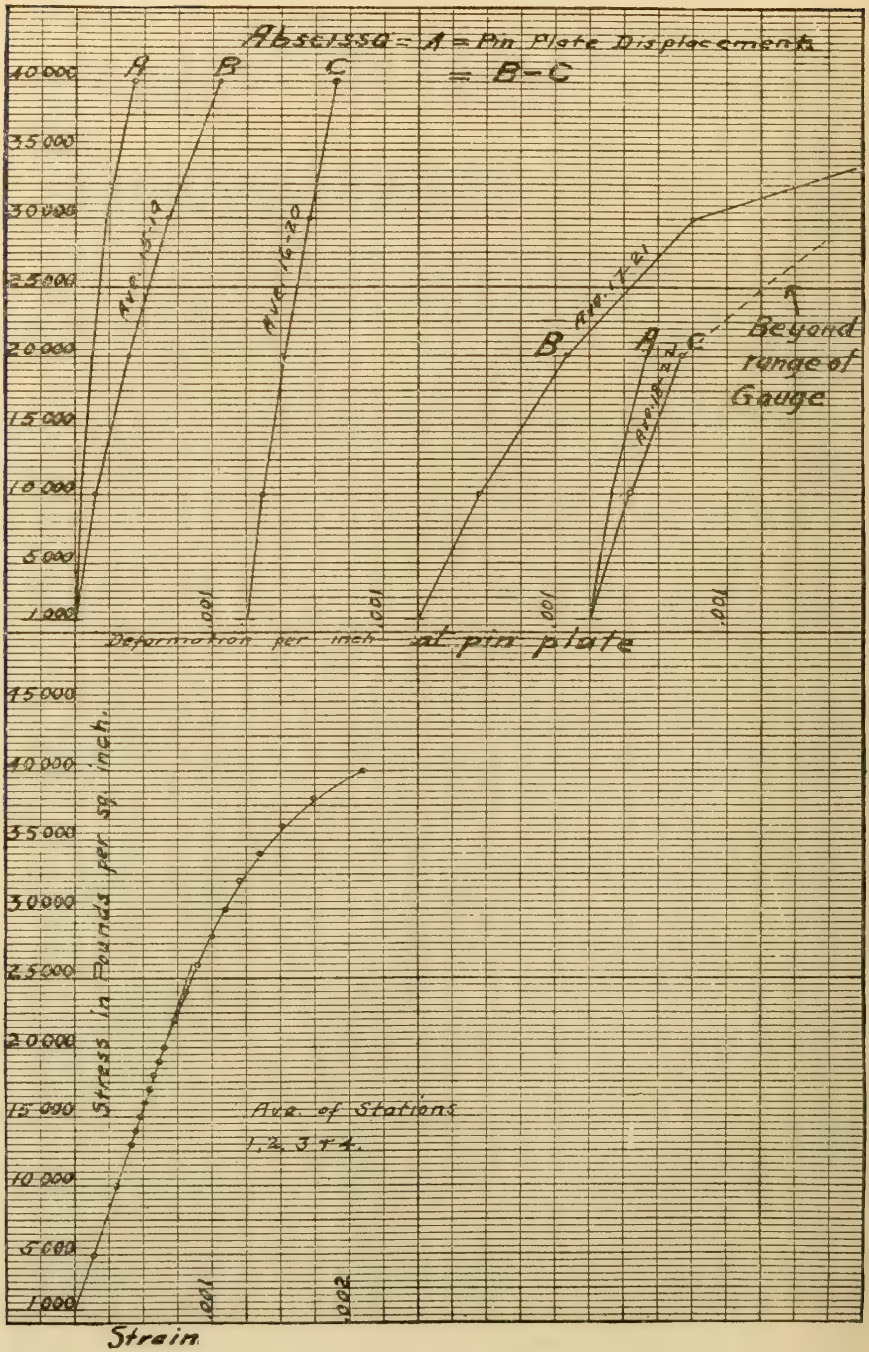


FIG. 32.—*Column 31HC1 (carbon steel)*

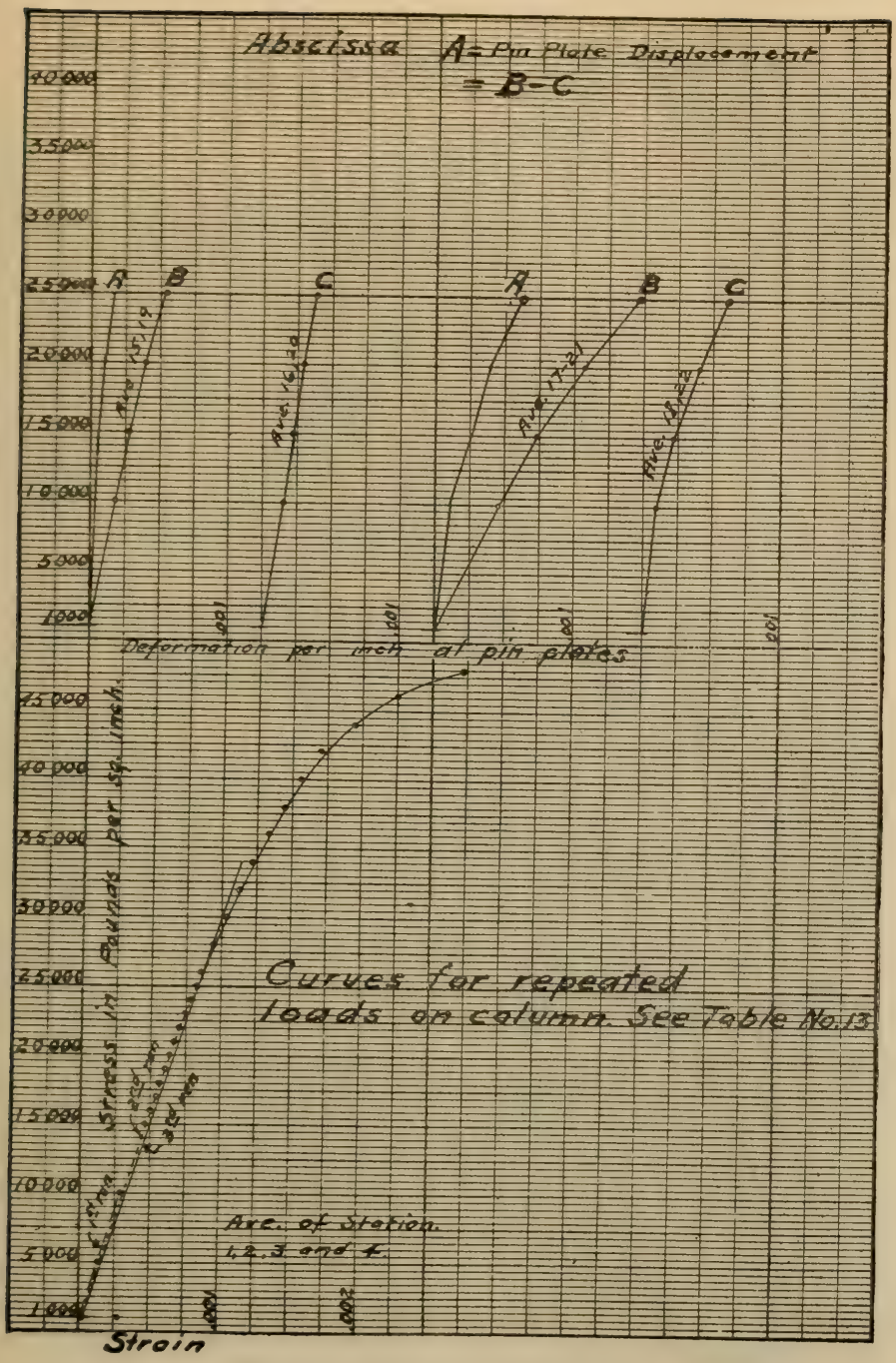


FIG. 33.—*Column 32S1 (silicon steel)*

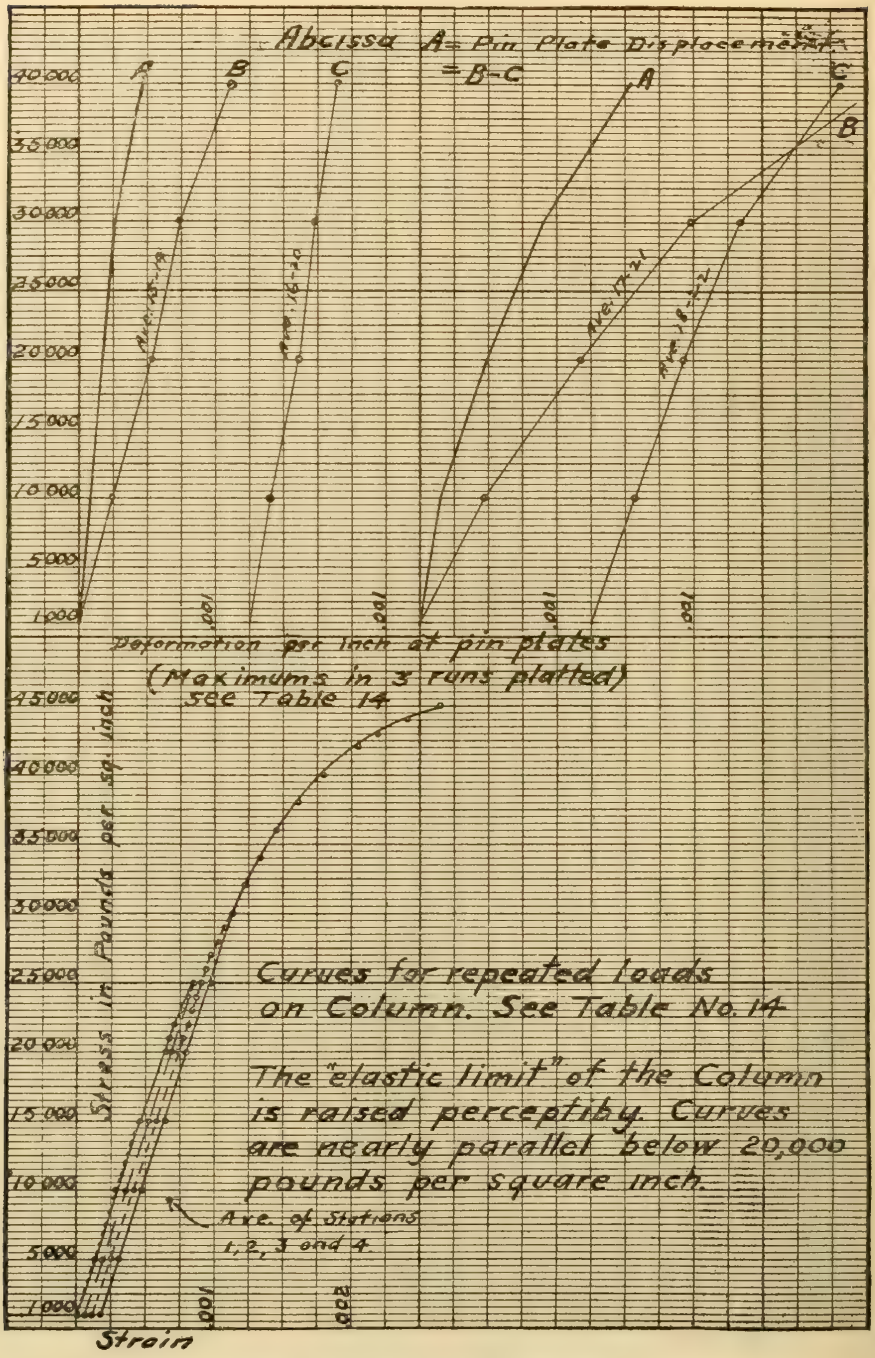


FIG. 34.—*Column 34CS1 (chrome steel)*

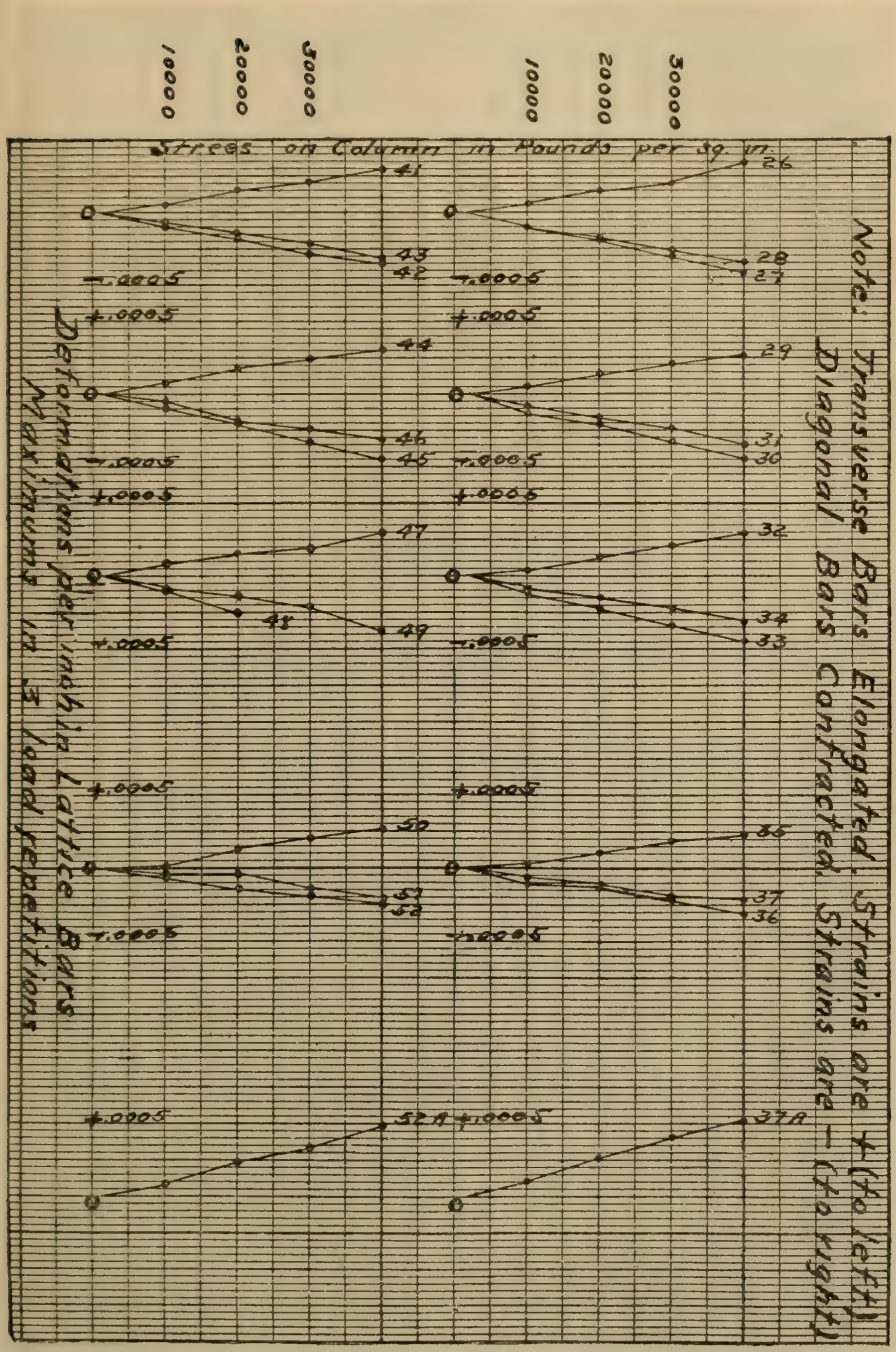


FIG. 35.—*Column 34CS1 (chrome steel)*

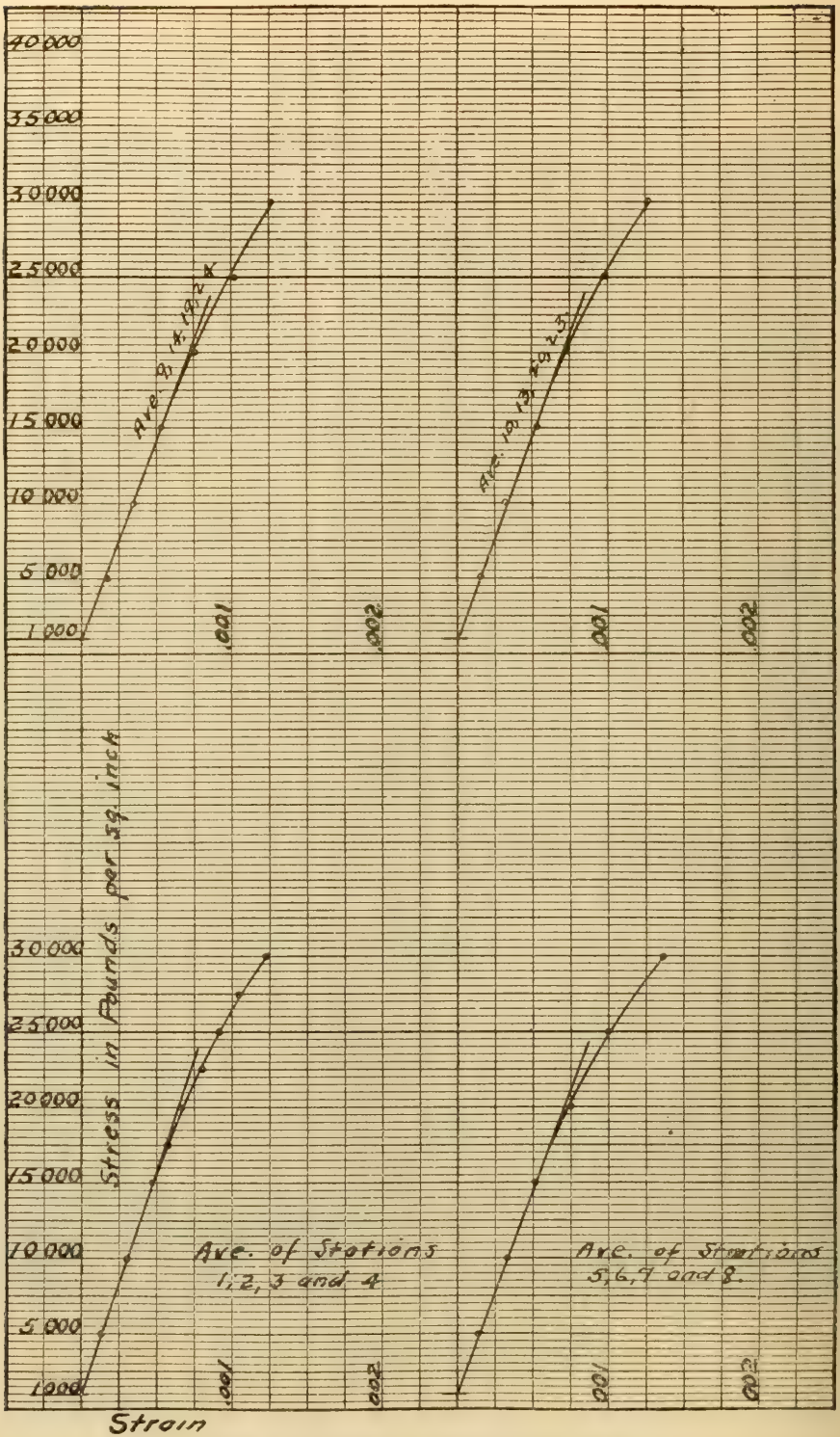


FIG. 36.—*Column $US_2 MS_1$ (carbon steel)*

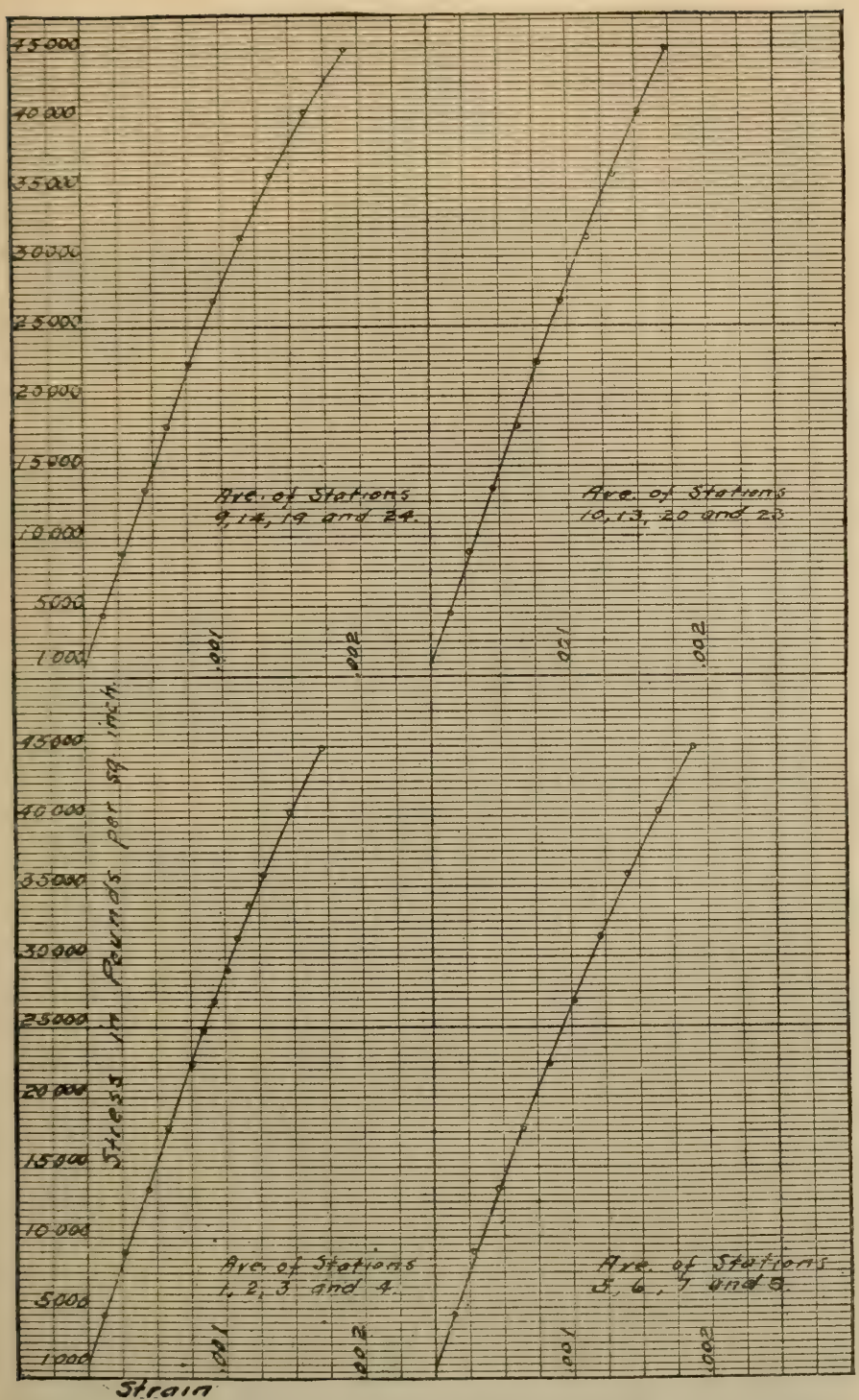


FIG. 37.—*Column* $US_2\,MS_1$ (*Mayari steel*)

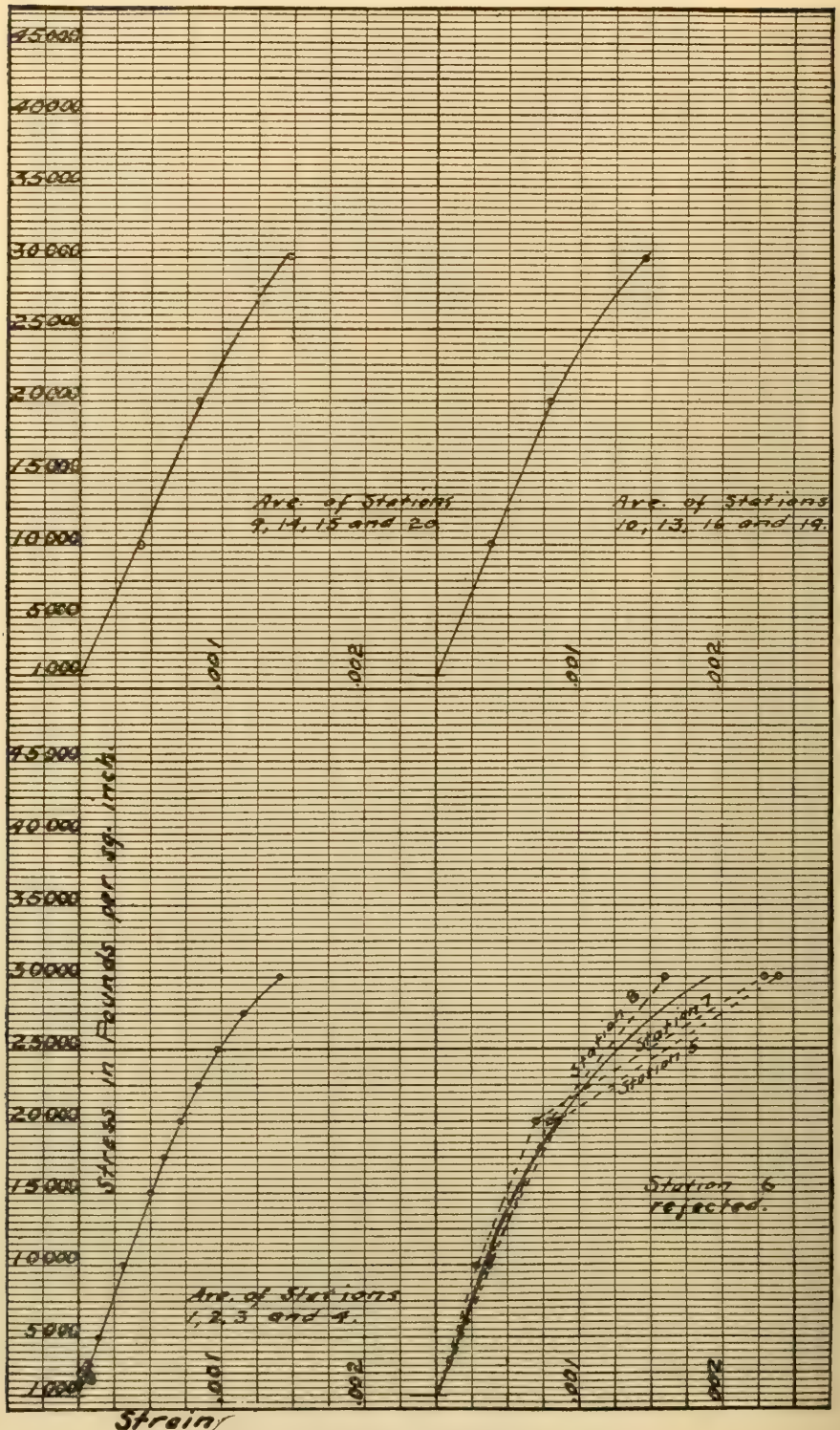


FIG. 38.—*Column U_2 M_1 (carbon steel)*

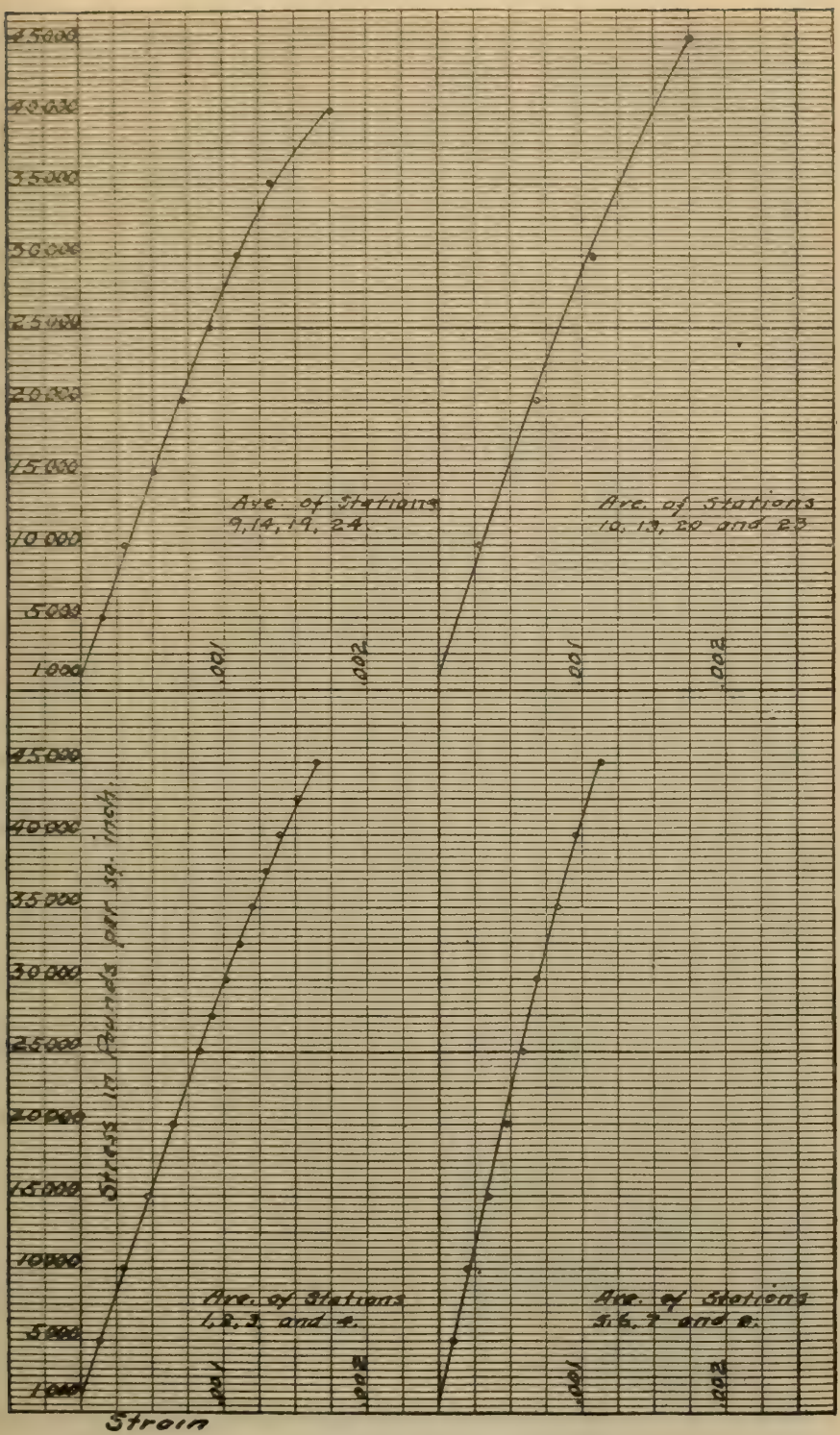

Ave. of Stations 9, 14, 19, 24.
Ave. of Stations 10, 13, 20 and 23
Ave. of Stations 1, 2, 3, and 4.
Ave. of Stations 5, 6, 7 and 8.
Stress in Pounds per sq. inch.
Strain

FIG. 39.—*Column U_2 M_1 (Mayari steel)*

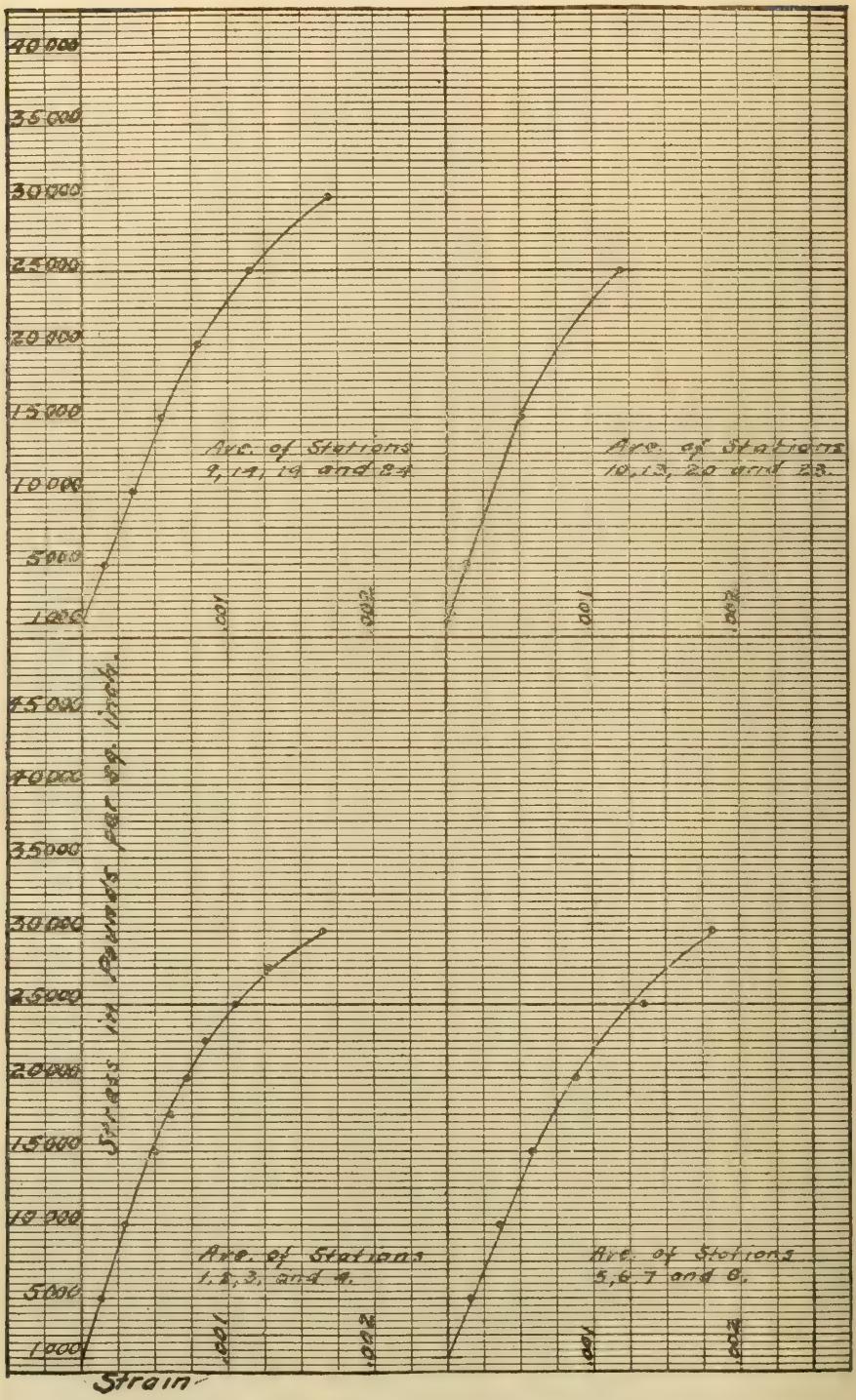


FIG. 40.—*Column LC_0 LC_1 (carbon steel)*

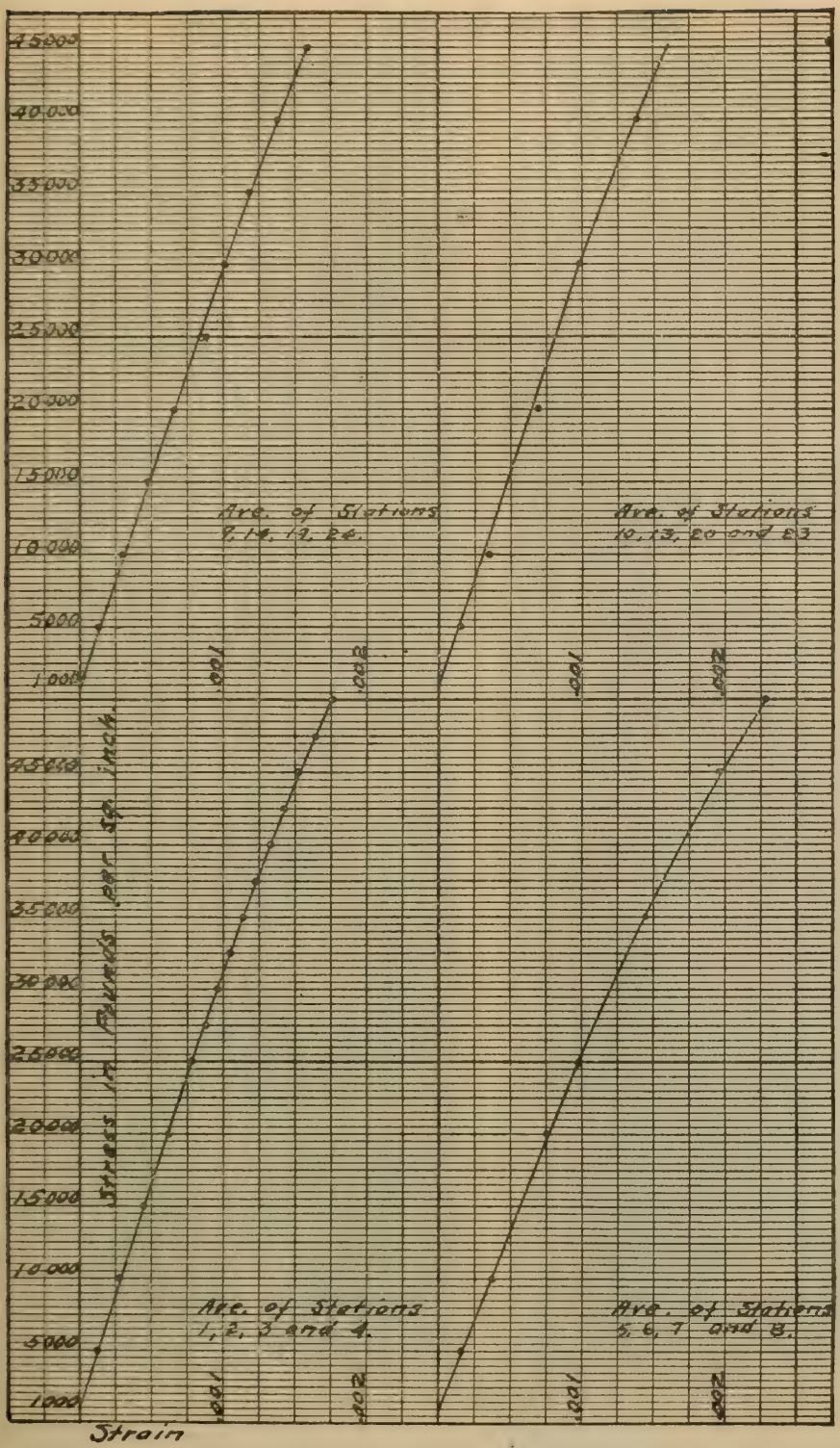


FIG. 41.—*Column LC_0 LC_1 (Mayari steel)*

VIEWS OF THE COLUMNS AFTER FAILURES.

The photographs from which Figs. 42 to 59 were made, with a few exceptions, were furnished through the courtesy of the American Bridge Co. and the Pennsylvania Steel Co.

In the case of the columns failing locally at the ends, the failures were very abrupt, and occurred practically simultaneously with the maximum loads obtained. In the case of the other columns, the amounts of distortions were as a rule somewhat in excess of those which occurred at the points of maximum loads. The pressures were applied continuously for several minutes after the maximum loads were obtained in order to accentuate the characteristic distortions of the column structures.

Attention is called to the continuous deflection curves of the columns of the Metropolis Bridge, and to the behaviors of the lattice bracing in all the columns. The characteristic slipping of the pin plates is well shown but in a slightly exaggerated degree by the white lines of Fig. 43, the "stepping" being a little more pronounced than that actually occurring under the maximum load.

FIG. 42.—*Columns U_2U_3 and U_8U_9 (nickel steel)*

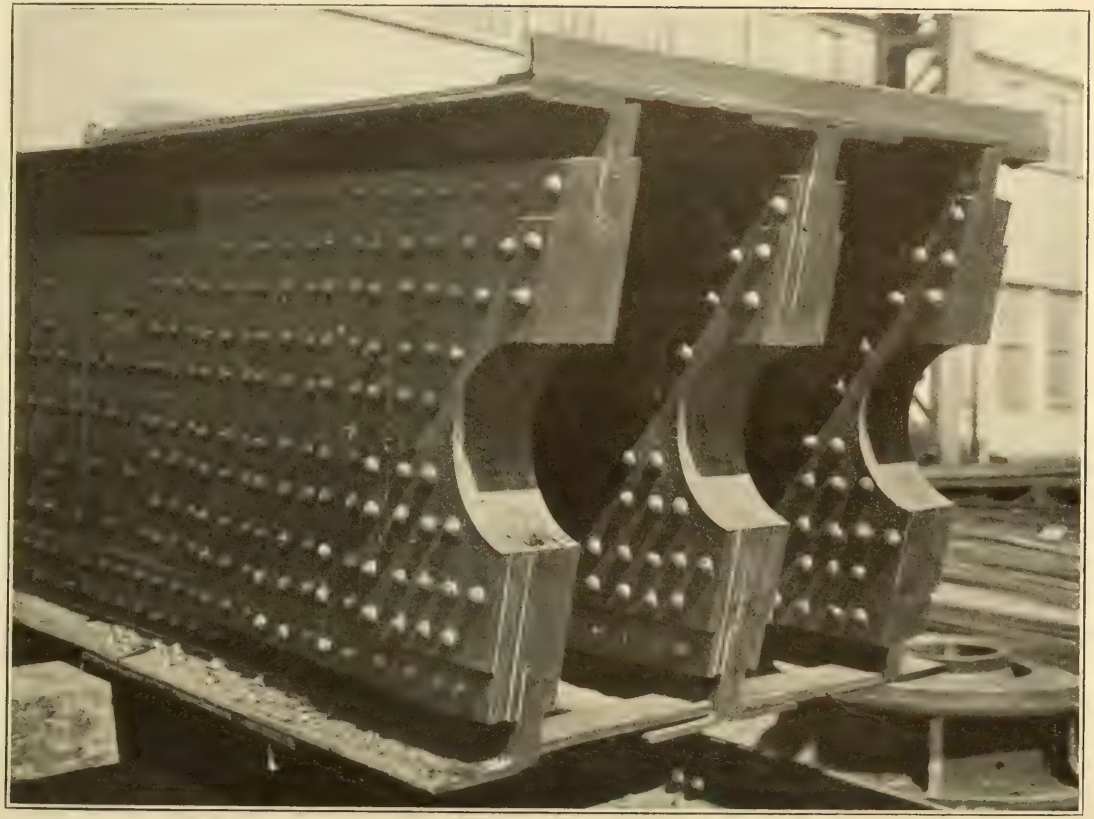


FIG. 43.—*End view of U_2U_3 after testing, showing movement of pin plates*

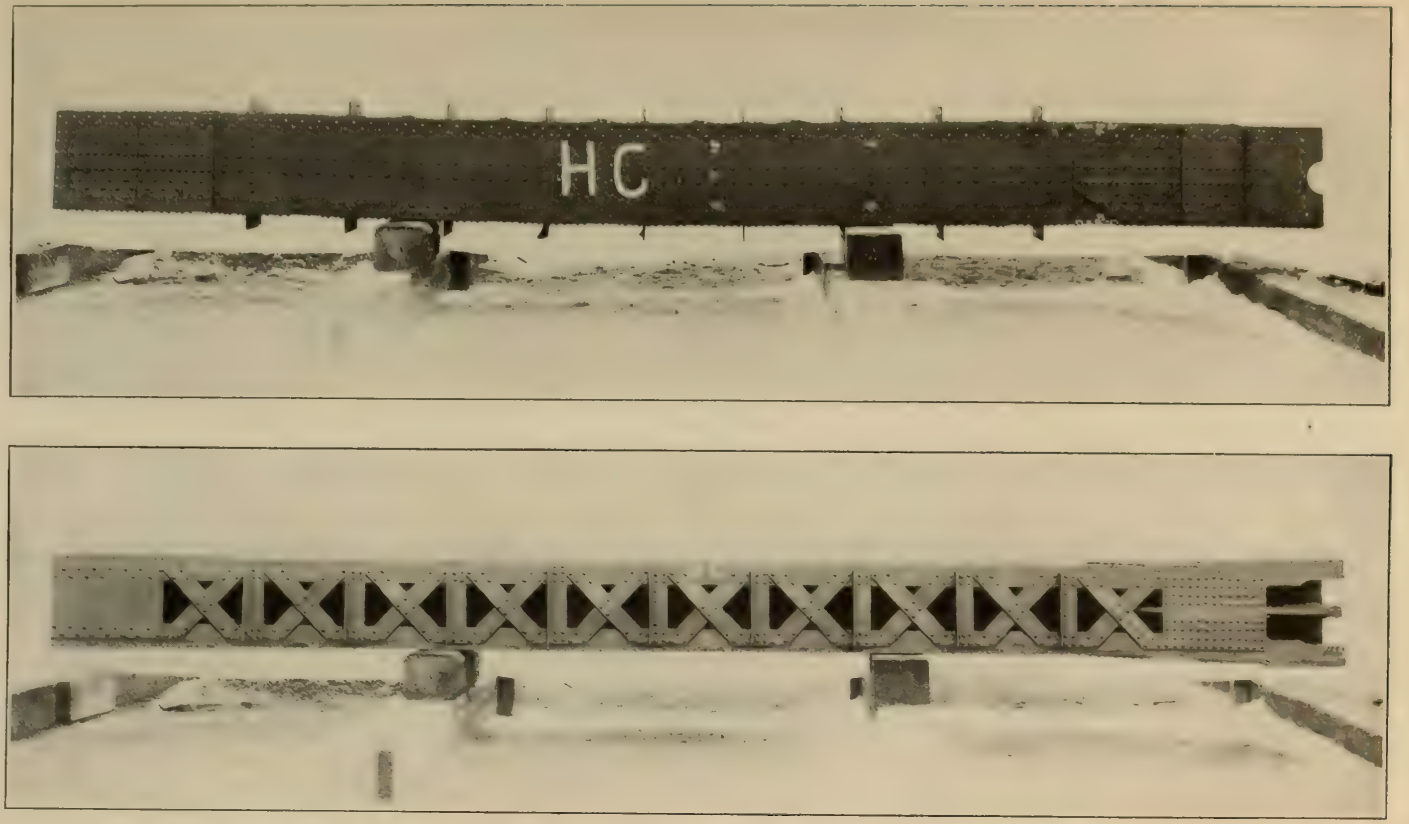


FIG. 44.—*Column HC (carbon steel)*

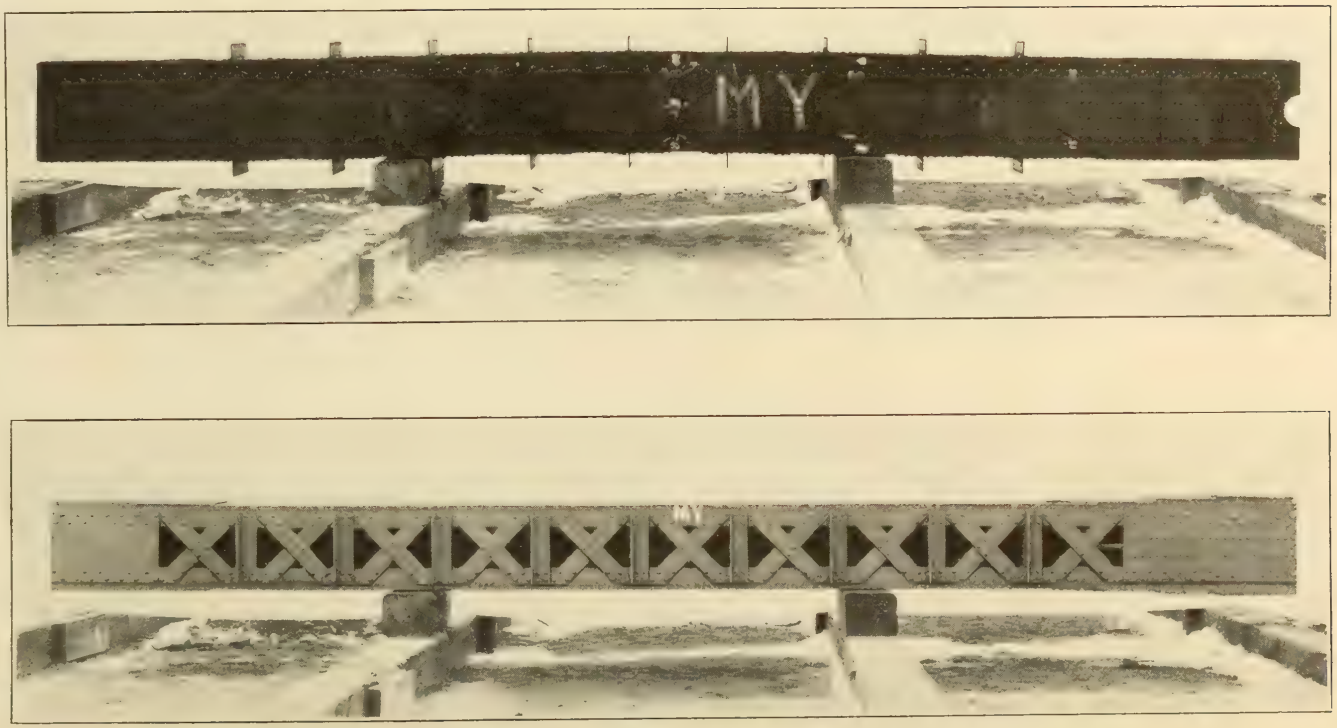


FIG. 45.—*Column MY (mayari steel)*

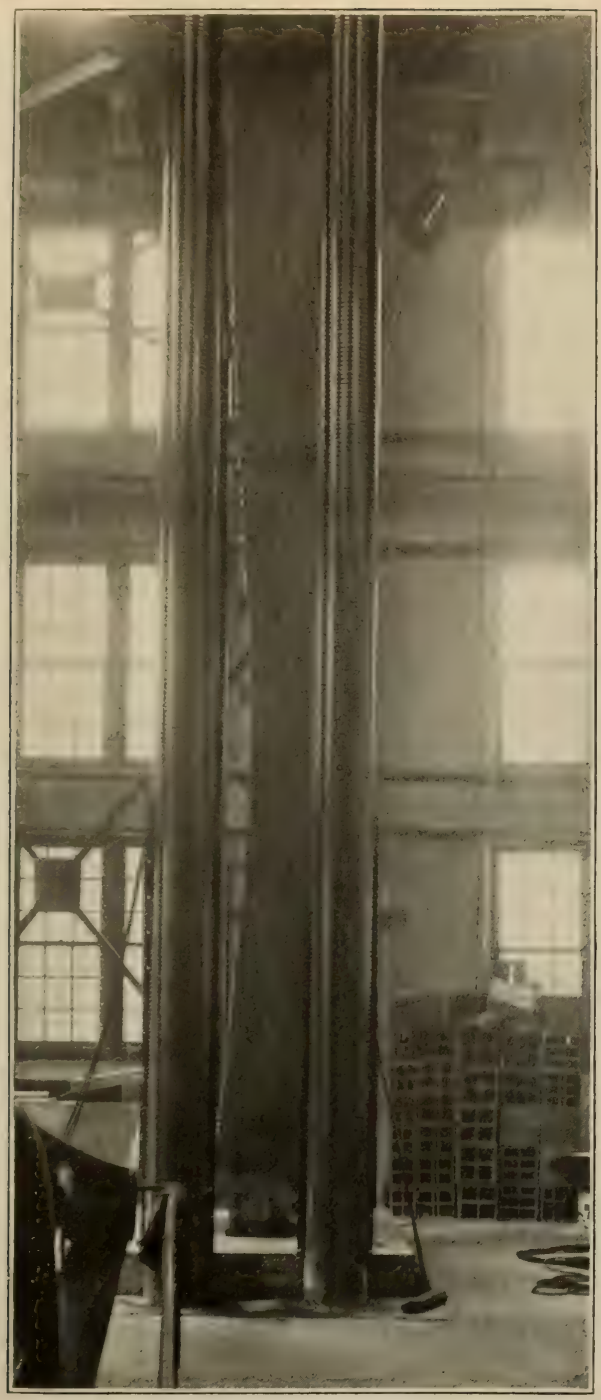


FIG. 46.—*Column 31IIC (carbon steel)*

FIG. 47.—*Column 31HC (carbon steel)*

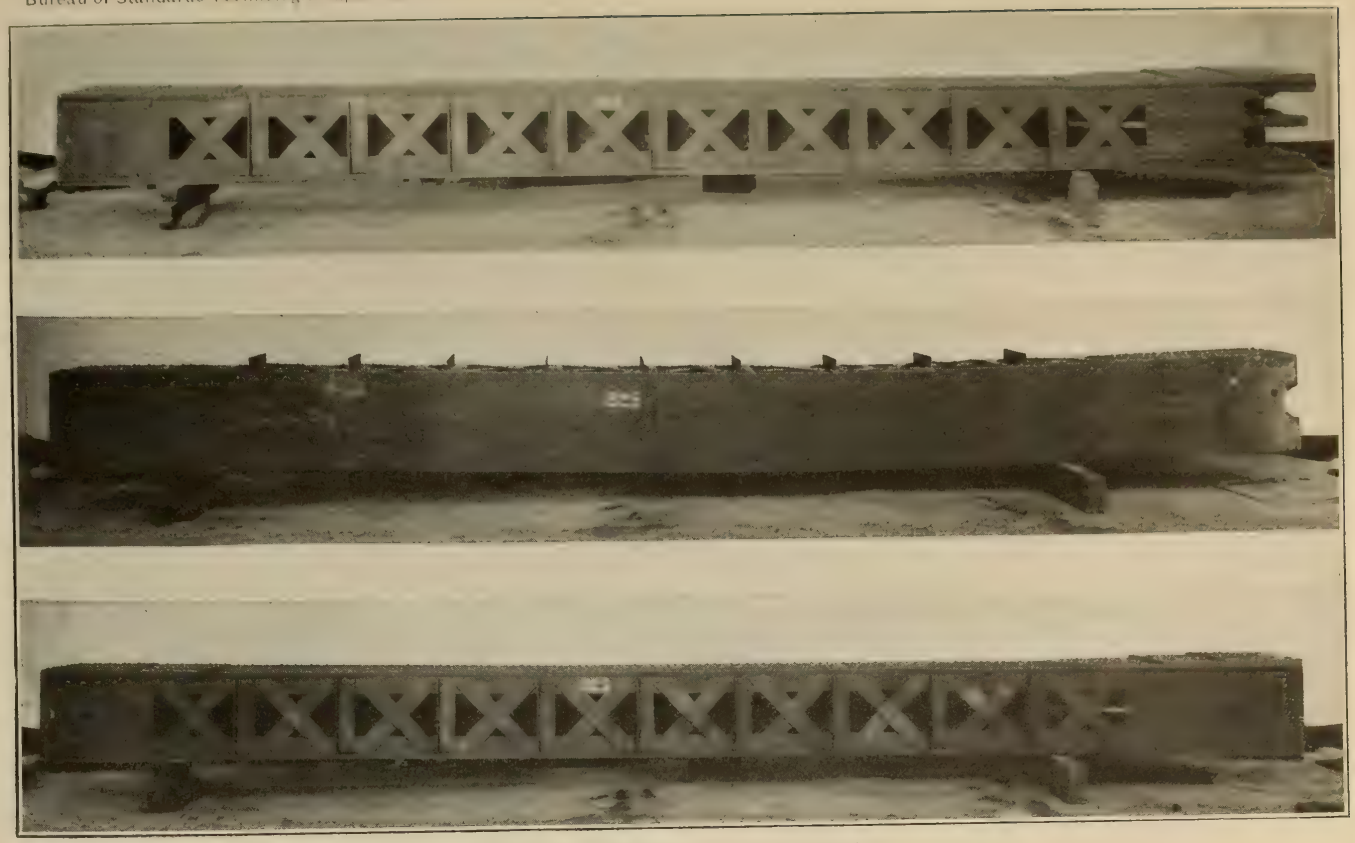


FIG. 48.—*Column 32S (silicon steel)*

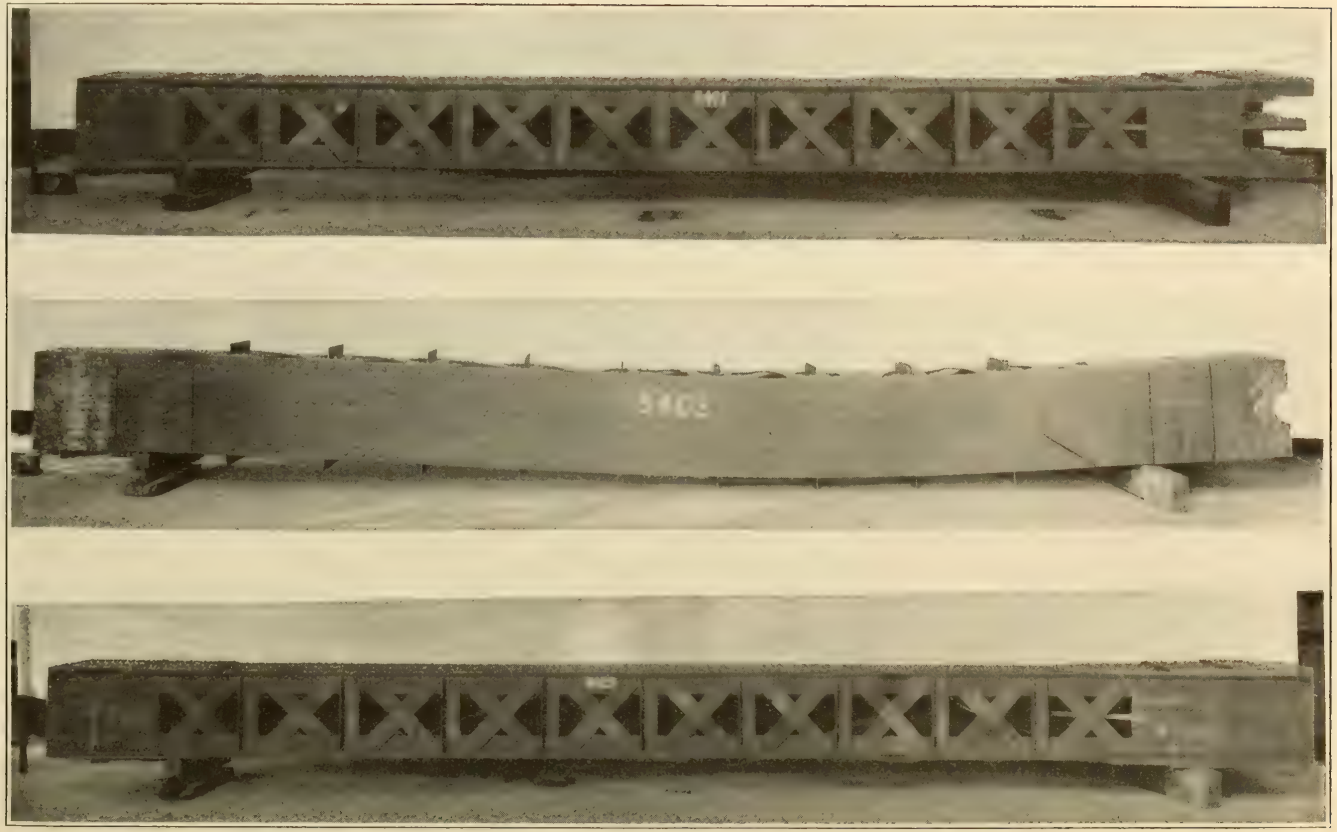


FIG. 40.—*Column 34CS (chrome steel)*

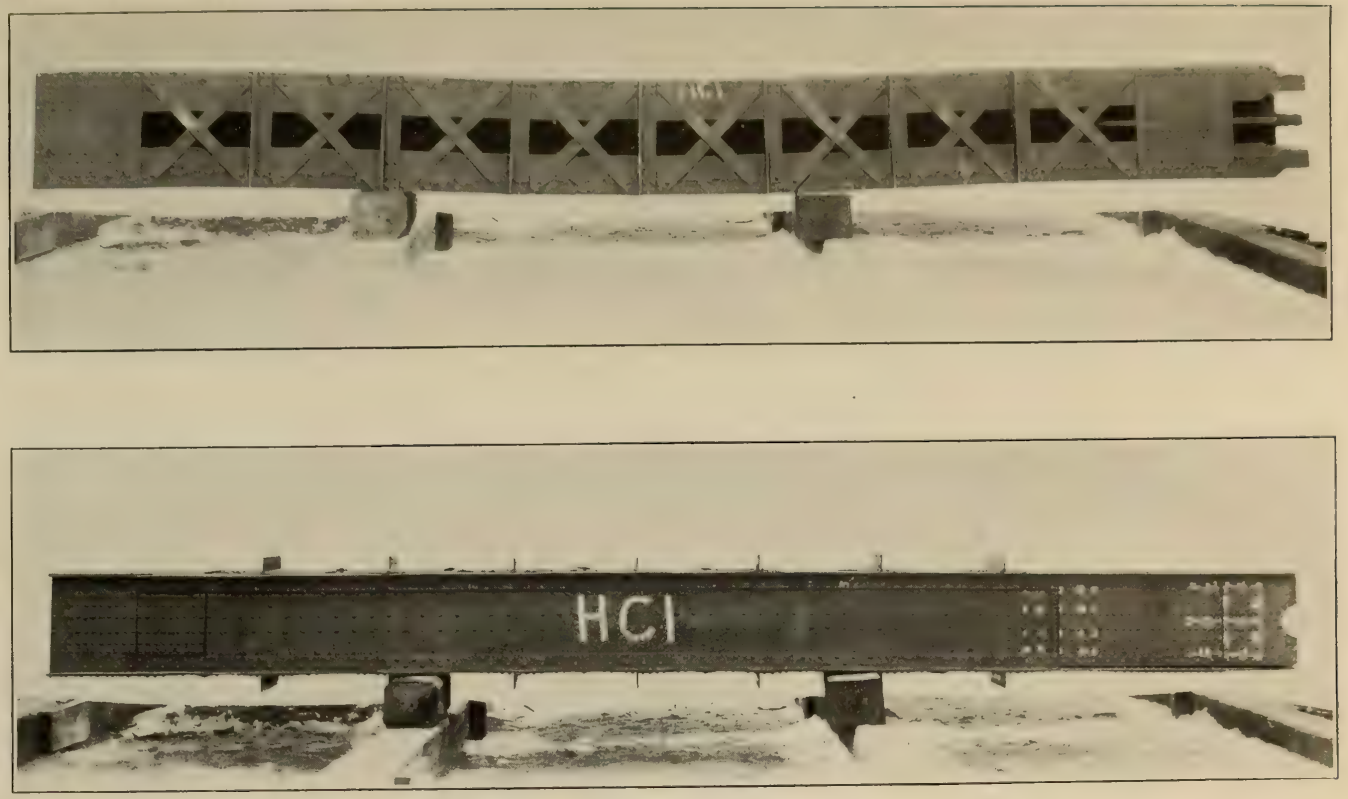


FIG. 50.—*Column HC1 (carbon steel)*

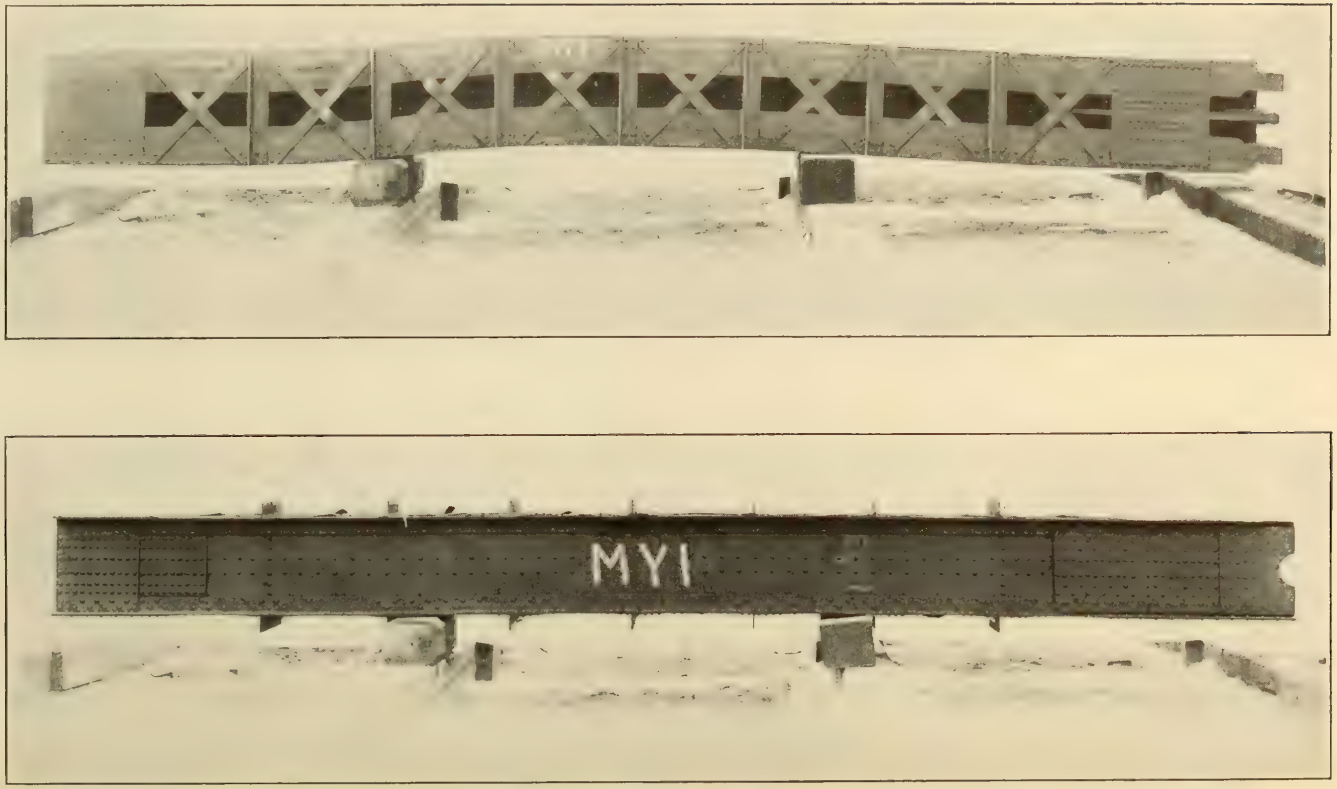


FIG. 51.—*Column MY1 (mayari steel)*

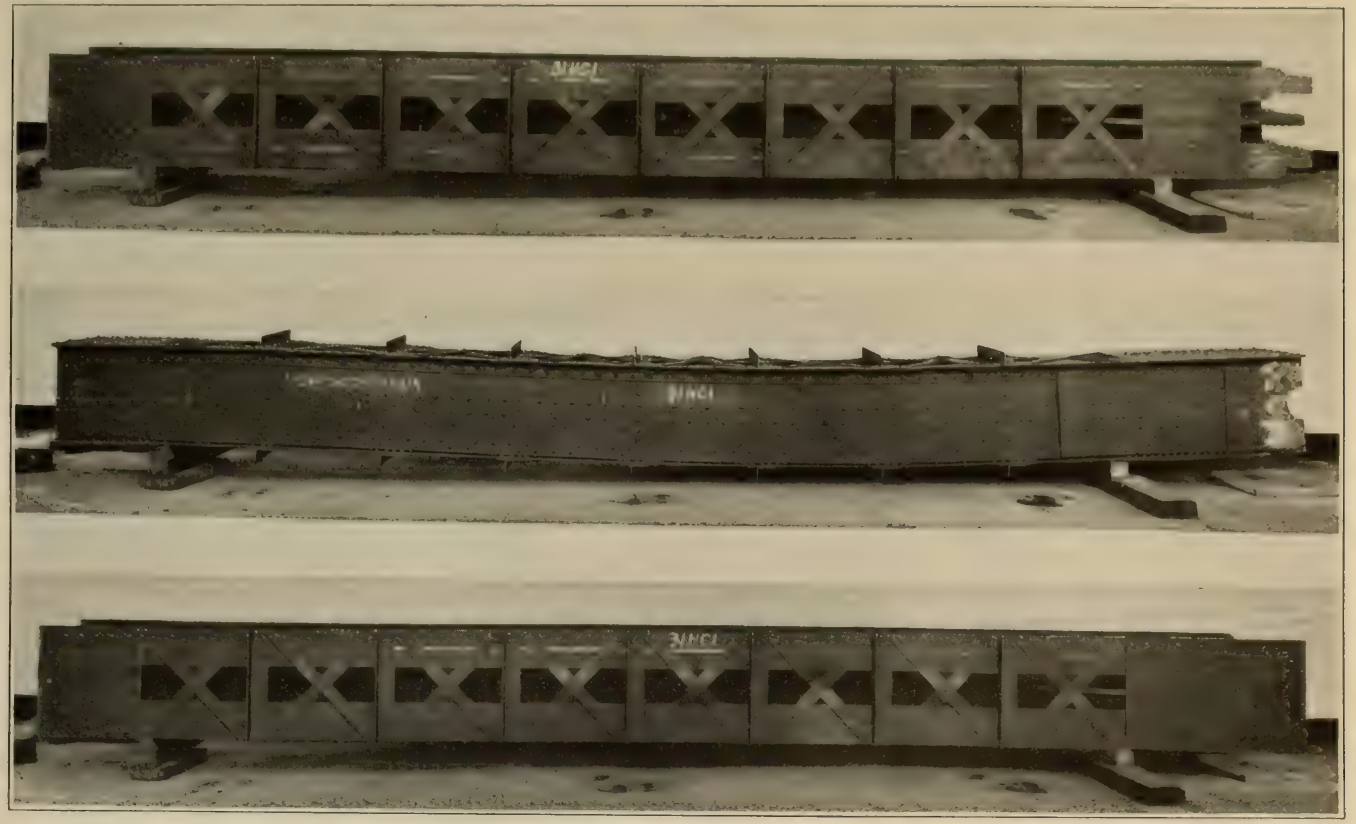


FIG. 52.—*Column 31HC1 (carbon steel)*

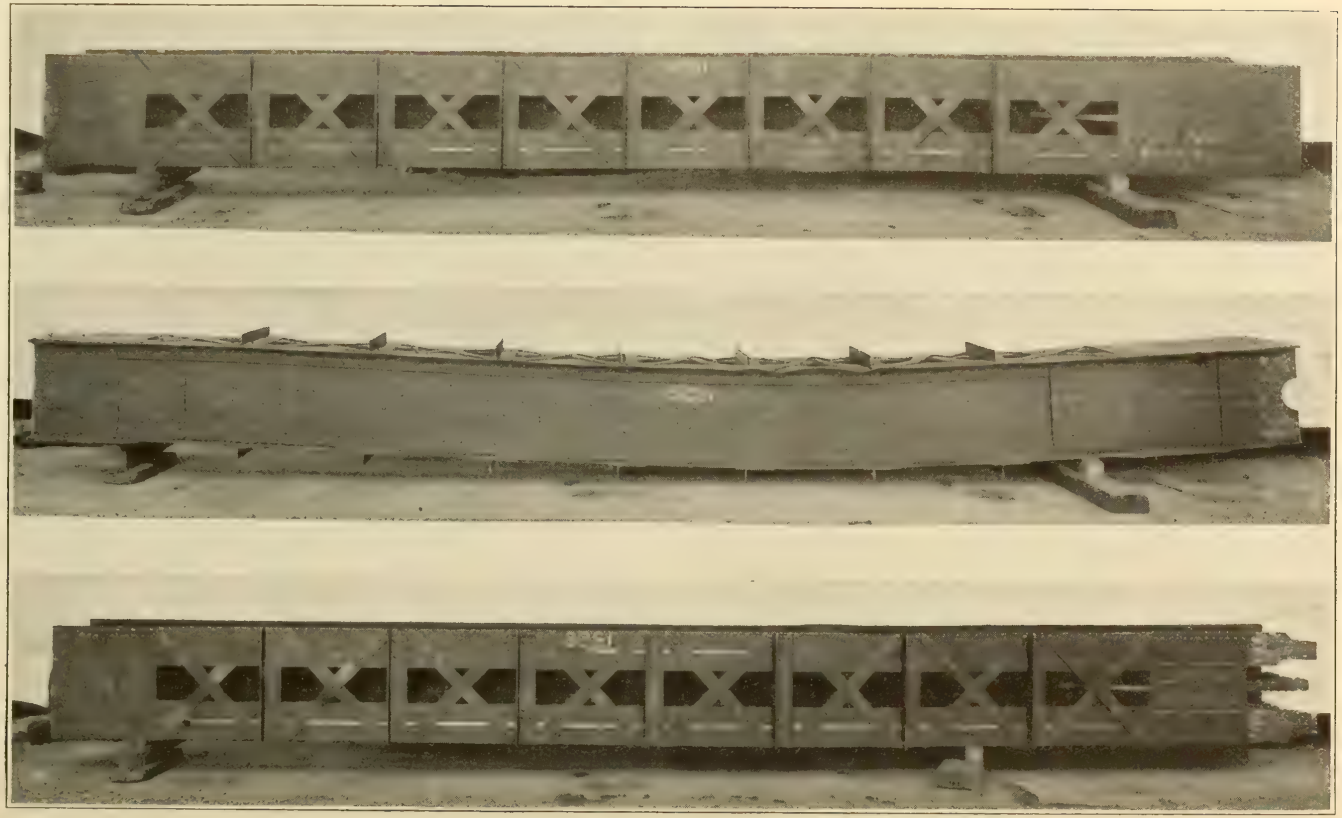


FIG. 53.—*Column 32S1 (silicon steel)*

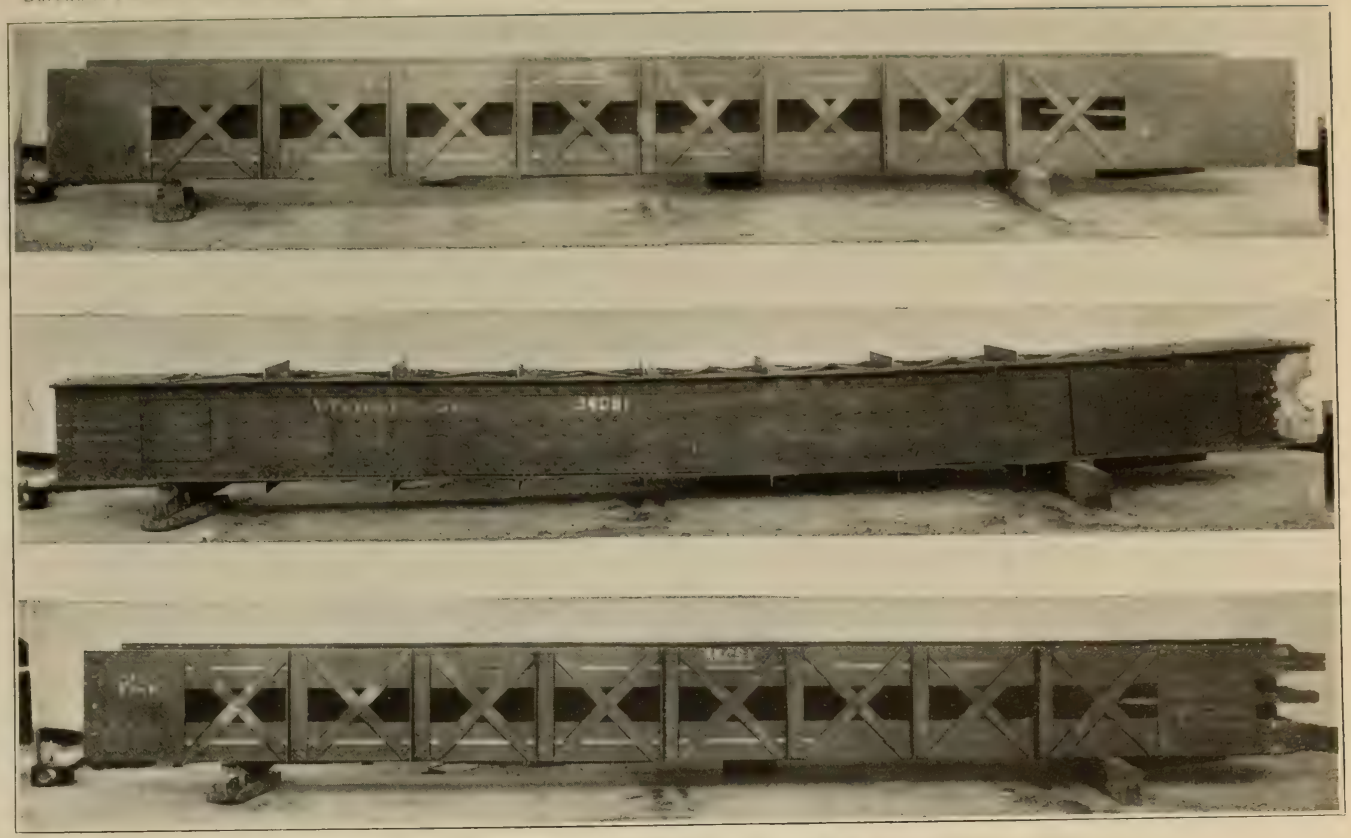


FIG. 54.—*Column 34CS1 (chrome steel)*

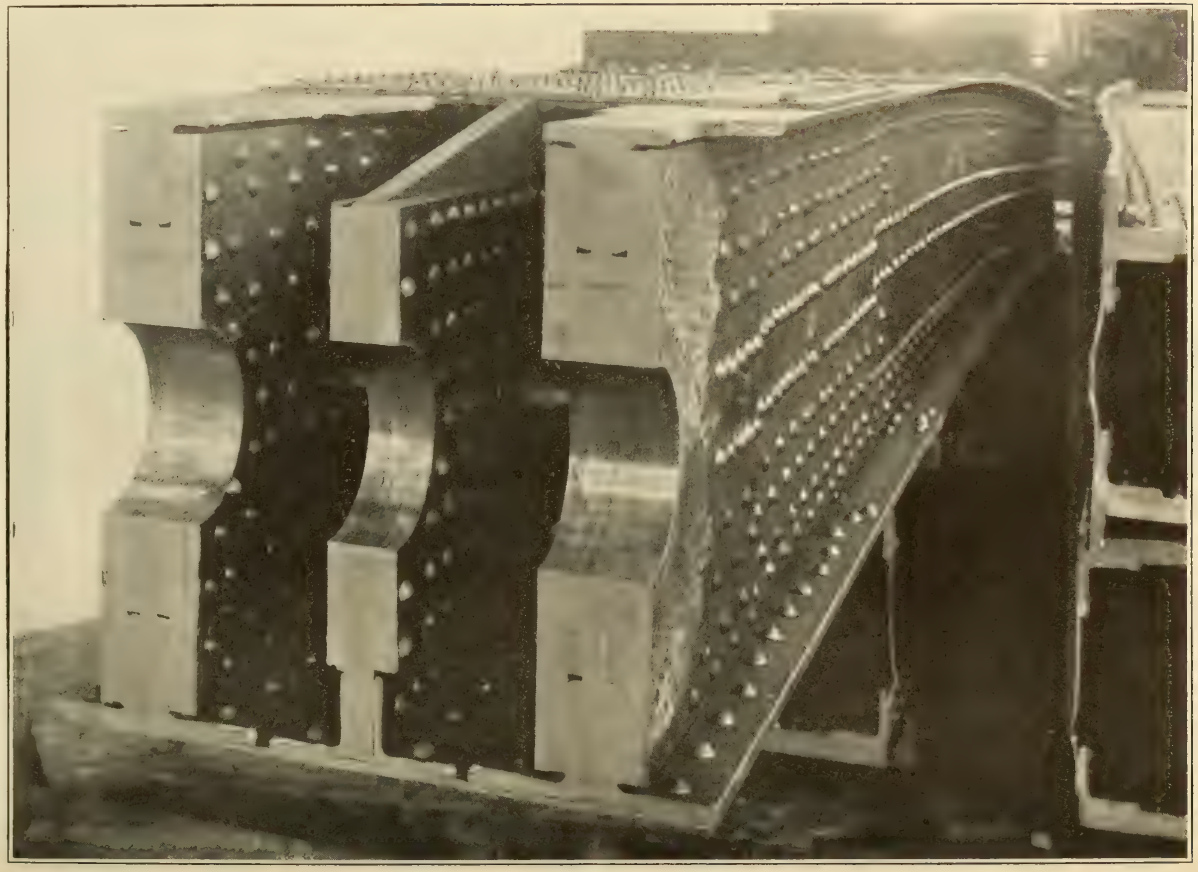


FIG. 55.—*Column 34CS1 (chrome steel)*

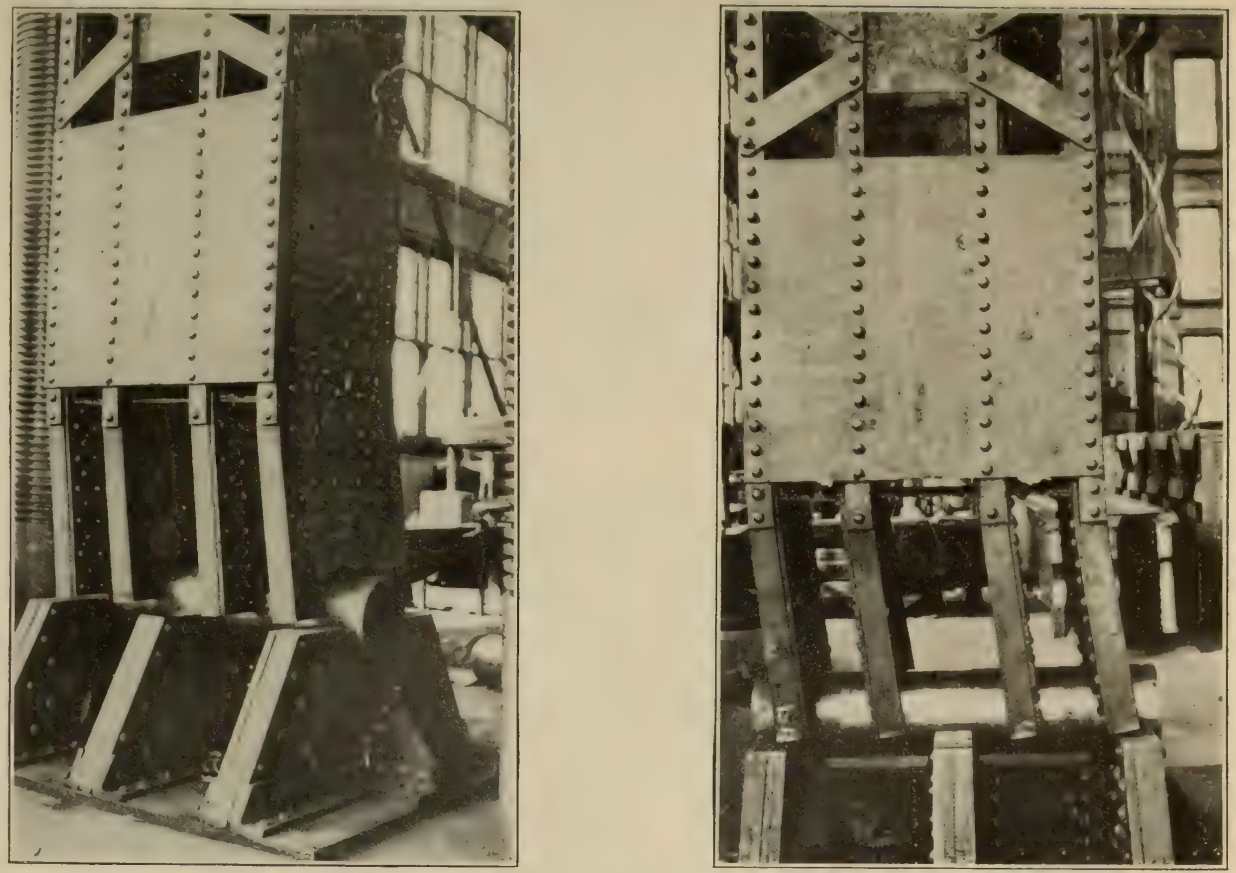


FIG. 56.—*Column US_2MS_1 (carbon steel)*

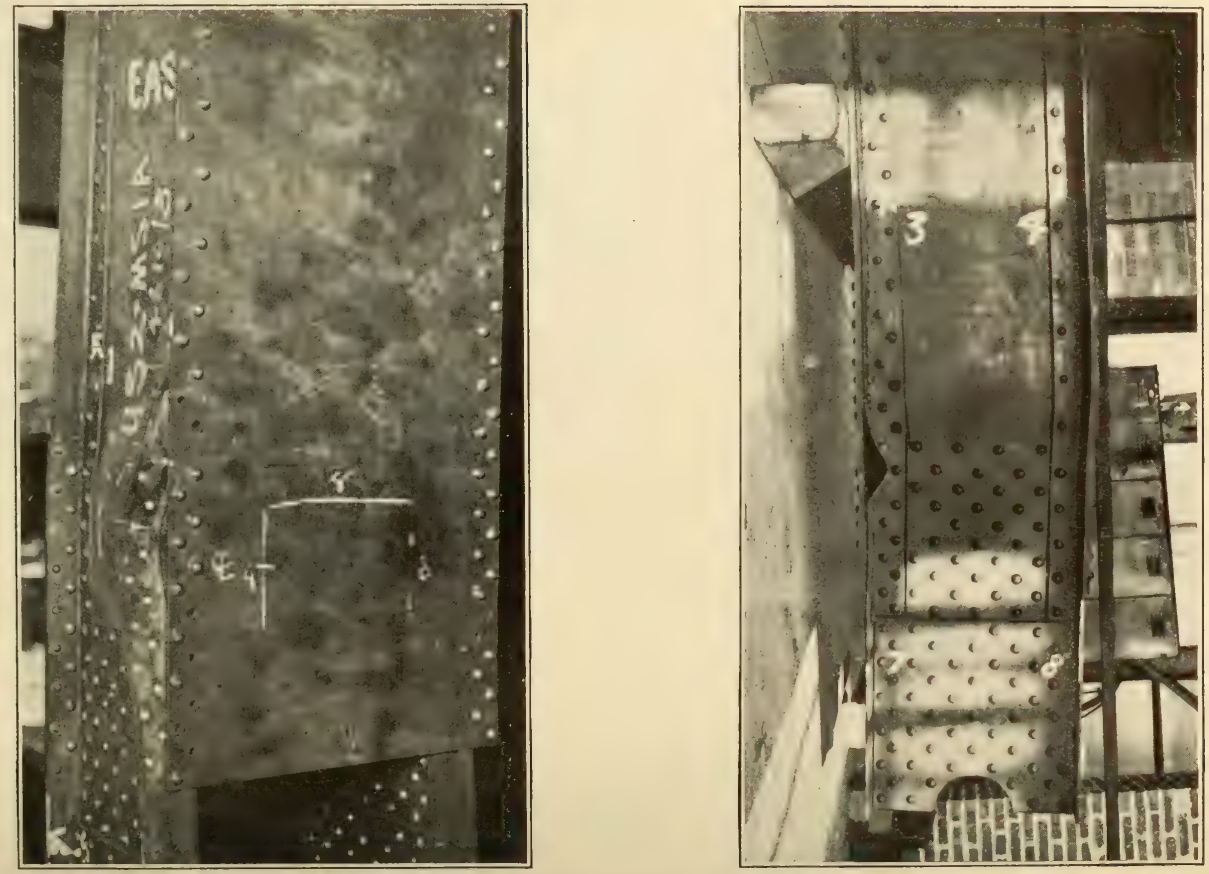


FIG. 57.—*Column US_2MS_1 (mayari steel)*

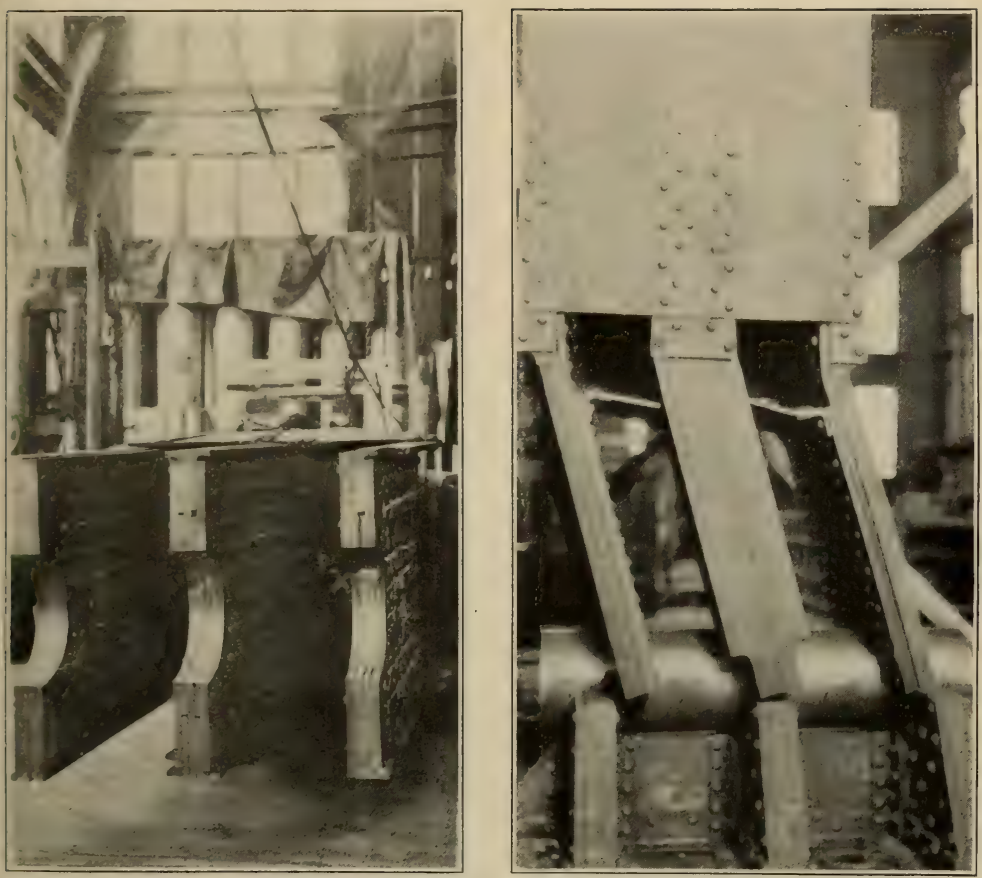
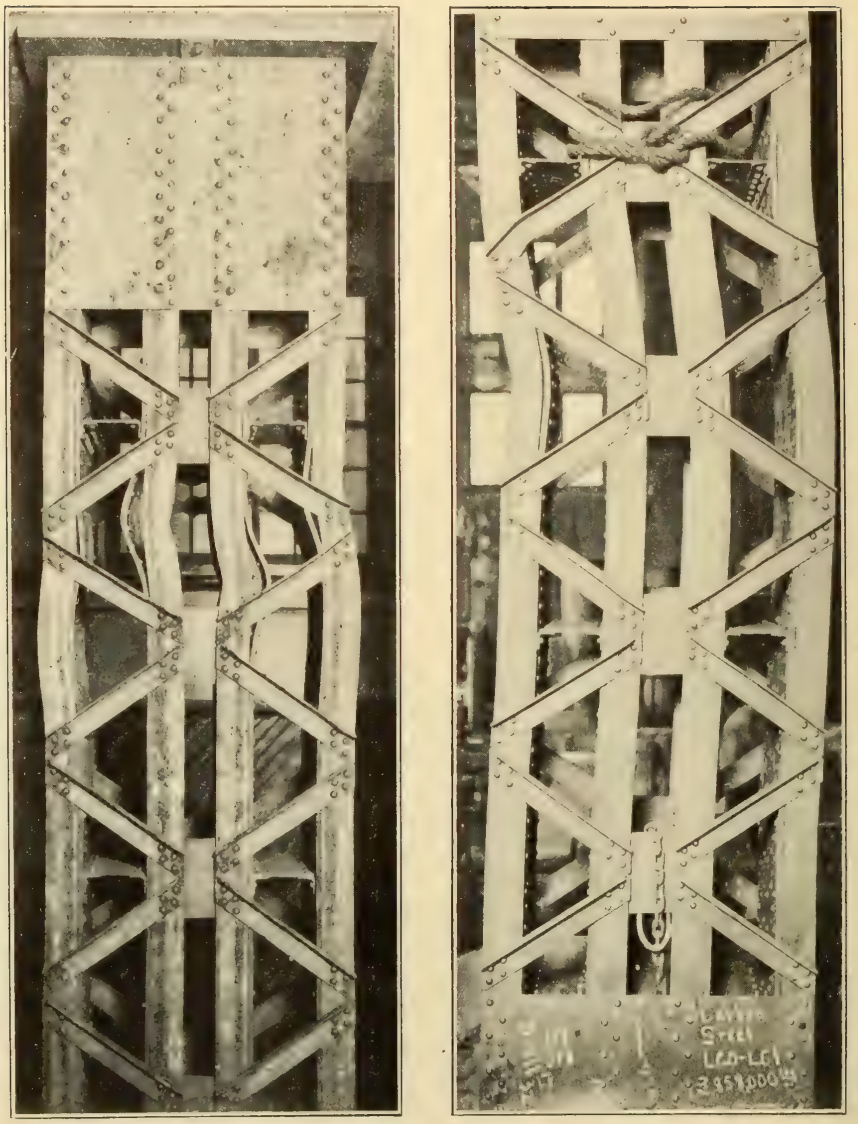


FIG. 58.—*Column U_2M_1 (mayari steel)*



Mayari Carbon

FIG. 59.—*Columns LC_0LC_1 (Mayari and carbon steels)*

IV. GENERAL DISCUSSION OF RESULTS OF TESTS

1. BEHAVIOR OF THE COLUMNS AS UNITS

It is the purpose of this discussion to analyze first the general laws of behavior of the columns considered as units. The behavior of the details will then be discussed. The test members will usually be treated comparatively and collectively in groups. The tables, stress-strain curves, and views of the columns after tests, already given in Part III, form the basis of the discussion. The main lines of research only are followed, and no attempt is made to give an exhaustive discussion of the results of the tests.

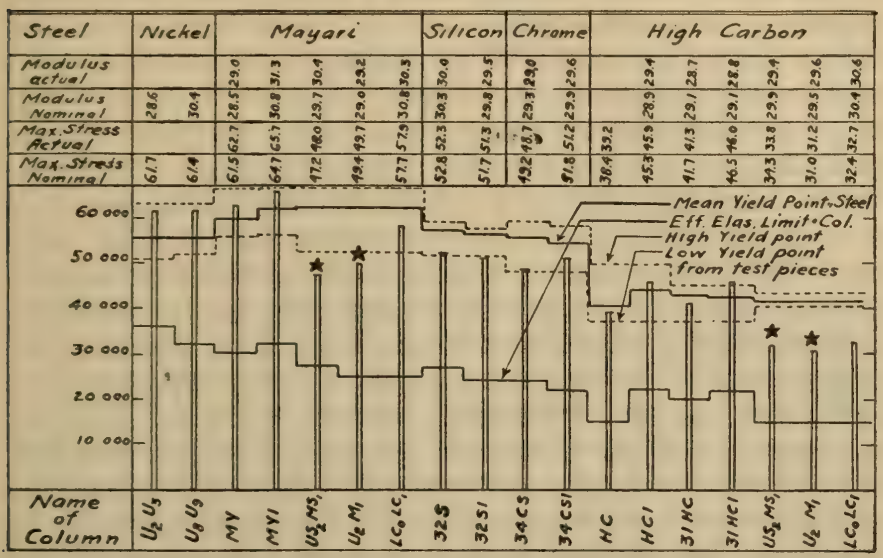


FIG. 60.—*Correspondence between maximum loads and yield points of steel*

(*a*) *Relations of Loads at Failure to Yield Points of Steels.*—The analysis of the behavior of the columns as units is conducted upon the assumption that the applied loads on the columns are uniformly distributed over their respective cross sections. The stress determined in this manner may be considered a first approximation to the real stress distribution. An analysis of the laws of flexure will be given later.

A graphical representation showing the relation of the observed maximum loads to the yield points of the component steels is given in Fig. 60. The data have been plotted as ordinates in descending order with respect to the strengths of the various steels used in the construction of the columns. The observed load on a column at failure is divided by the nominal cross section of the shaft. (See Table 1.) This is recorded in Fig. 60 under the

heading "Maximum stress, nominal." The load at failure is again divided by the actual cross sections calculated from the scale weights of the steel. This is recorded under the heading "Maximum stress, actual," and is also shown to scale by the heights of the respective bands shown in the figure. The heights of these bands in the case of columns $U_2 U_3$ and $U_8 U_9$ of nickel steel may be in error ± 1 per cent, as it was impossible to obtain the precise cross-sectional areas, the nominal areas being used instead. The relation of these loads to the yield points of the various component steels is to be considered.

The upper limit of loading which a compression member can sustain, whether it is a large column or a small test piece, is commonly held by engineers to be the sensible yield stress or so-called commercial elastic limit of the steel. Howard [12] has stated that it is impossible that the strength shall exceed this limit, because it is the point at which cold flow of the steel occurs. If the observed maximum load on a column of small slenderness ratio exceeds the yield stress, it may be inferred that there are some abnormal or indeterminate elements to be considered in the tests. Among such as may occur, for example, may be mentioned the restraining influence of the frictional stresses on the platens, a possible raising of the proportional limit by the cold working of fabrication, the lateral restraining influence due to the stress put on rivets in cooling, variations in properties of shapes, etc., with others, which will be discussed rather fully later, and such factors will cause some modifications in the theoretical values to be expected. On the other hand, it is equally important to consider, as has been stated by Waddell,[13] that when a member is efficiently designed and the $\frac{l}{r}$ reduction factor is duly taken into account the load should not fall below the true elastic limit of the steel.

The mean yield points as given in Table 2 are averages of 8 or 10 determinations made on tensile test pieces for the component shapes of each column. The high and low values for the different test pieces have also been recorded. It was impracticable to obtain the actual component yield points in respect to the positions and orientations of the different shapes in each particular column, and a special investigation of the influence of the variation of the yield point over a column cross section has long ap-

[12] Cf. Trans. Am. Soc. C. E., 73, p. 492. [13] Engineering News, Jan. 16, 1908, p. 62.

peared desirable. It is reasonable to suppose, however, that incipient failures first occur in the steel shapes having the lowest yield points; a local weakening of the columns takes place at this stress and progressive redistributions of load occur from time to time over the cross section. This inference is warranted by the slight variations usually perceptible in the rates of taking load, there being alternate increments and decrements in loads apparent on the scale beam, these occurring in small cycles of action as power is applied from the testing machine.

The curve showing the mean yield points of the columns as found from the different test pieces has been platted on Fig. 60 in order to show graphically its relation to the curve of corrected maximum loads at failure as found from the testing machine which is defined by the locus of the heights of the vertical strips. There is a fair agreement, it will be seen, with the stress at failure except in the case of certain columns (starred in Fig. 60) which failed locally at the ends and two others, the columns LC_0 LC_1 of Mayari and carbon steels, respectively, which strictly did not fail as units. There is a deviation in some cases of several thousand pounds per square inch, as, for instance, in the case of the nickel steel members U_2U_3 and U_8U_9. It will be found, on the other hand, that if the high and low values of the yield points from Table 2 are also platted on the diagram, the extreme curves define a zone which includes the locus defining the failures of the columns at maximum loads for all columns failing as units, excepting 32Si. (silicon), which was just outside the lower edge of the belt and 31HC1, which was just over the upper edge. The points above mentioned tend to confirm the remarks of the late C. C. Schneider, made some three decades ago, relative to the importance of considering the elastic limit instead of the ultimate strength in design, the well-known experiments by Considere [14] confirming this and the later emphasis which has been placed upon the matter by Howard [15] in some large column tests which he recently made.

The relation of failure to yield point may be stated, perhaps, a little more succinctly. The average value of the maximum loads of the 12 columns failing as units will be found to differ but one-half per cent from the grand average of the tensile yield points of the steels as found from the separate groups of test pieces. The difference in absolute value is about 200 pounds per square inch. The range of the separate deviations taken in absolute values per

[14] Johnson's Materials of Construction, 4th ed., p. 361. [15] Trans. Am. Soc. C. E., 73, p. 492.

cent is from 3.7 to 12.5. It is believed to be a reasonable induction from the above considerations that the failure of a large column of small slenderness ratio will occur at or near the yield point of the steel, as is commonly the case with a small test piece in tension or compression. The range in variation between high and low limits evidently depends upon that found from the independent tests of the component steel shapes. If this range can be constricted in practice, the predicted strength of a column may doubtless be made to agree closer with the results of experiment than heretofore.

The ranges between the high and low yield points of this investigation are not as small as can be obtained when special selections are made of the heats by the bridge companies. However, they may be considered reasonable variations from the mean and are fairly representative of the conditions which exist in engineering practice. It is advisable, however, in estimating the maximum load of a column of small slenderness ratio at or near the yield point of the material that the range between the "high" and "low" values should be considered. While the values used may doubtless be weighted proportionately to the strengths of the various steels to give a slightly closer prediction of average range of any particular maximum load from the mean yield point than has just been given, particular refinements of calculation appear unnecessary because of the effect of other variables which influence the apparent maximum loads at failure, and which will be discussed later.

(*b*) *Proportional Limits of Columns.*—It has been seen from the separate stress strain curves plotted for each column, Figs. 22 to 41, that the constant proportionality of stress to strain ceases at a point which is some 50 per cent of the maximum stress at failure which has already been shown to be near the yield point of the material. C. P. Buchanan [16] in his analysis of the tests for the Pennsylvania Lines called this critical point of the curve the "elastic limit" and reserved the name "yield point" for that point somewhat higher on the curve where there again occurs a scarcely perceptible change in the rate of slope of the curve above his "elastic limit" as above defined. The difference in stress is usually about 2000 to 3000 pounds per square inch in the interval. It is considered important by bridge engineers that the ensemble of working stresses, dead, live, snow, impact

[16] Engineering News, 58, p. 685; Dec. 26, 1907.

stresses, etc., when appropriately combined shall never exceed the lower critical point which in this paper is called the proportional limit. In the event of such contigencies occurring, there would undoubtedly be a perceptible change in the initial cambering of the lower chord of the bridge and a redistribution of stresses in the truss differing from that originally calculated by the designers.

The yield point above the proportional limit, especially for the harder steels, was too poorly defined in these experiments to justify any attempts to determine it. There is no discountinuity present in the slope of the curve such as occurs in the case of the tension test piece. Howard in his published statements seems to confirm this whereas Prichard has stated that he has found such a yield point in very high carbon steels. The curve which is the locus of the ordinates representing the proportional limit from each column test is shown also in Fig. 60.[17] The average value of these proportional limits expressed with reference to the observed maximum stresses is 48.4 per cent, and with reference to the tensile yield points of the steels is 48.6 per cent.

It should be stated that the difficulties of obtaining the value of the proportional limit for a column are comparable to those of finding the proportional limit in a tensile test. The range from the mean can be expected to be at times relatively large in columns of built-up material and rather delicate recording instruments would be needed for rigorous determinations. A study of the causes which determine the height of the proportional limit on the curves will be further and more appropriately analyzed in connection with the subject of initial strain. It will be shown later that the deviation from the right line begins at the initial load. The point taken simply defines that stress where the change in rate of stress to strain becomes sensibly apparent.

(*c*) *General Remarks on the Maximum Loads.*—Considering the relations of the maximum loads to each other the data show (see Fig. 60) that the nickel and Mayari steel columns fail at from 2000 to 6000 pounds per square inch above their respective yield points, the silicon and chrome steel members about the same stress below, while the carbon steel specimens fail very close to the particular yield points of their respective steels. Considering the yield point as a datum of unity the nickel steel members have the highest ratio of strength to yield stress. The two columns

[17] These values of the proportional limits, as shown by the curve of Fig. 20, are conservative.

of Mayari steel have the greatest loads in absolute value. The yield point of the Mayari steel is slightly above that of the nickel steel, and in this respect the presence of the chromium and 1.6 per cent nickel in the Mayari steel makes a favorable showing in relation to the nickel steel.

In the columns of the Memphis Bridge, (see Fig. 60, columns "starred") already mentioned as failing at the ends, the space for eyebar entrance necessitated rather long unsupported forked ends. Although calculation would appear to indicate a reasonable "short column" resisting section at the pin plates, the matter was evidently one which could only be ascertained by the designers experimentally. The two members LC_0LC_1 failed in the direction of the major principal axis of the cross section, the radius of gyration being relatively larger than in the direction at right angles. (See Table 1.) It will be noted that the effective strength of the ribs acting as struts between lattice joints is less as determined experimentally than the resistance of the column as a unit would be expected to be from calculation, and this undoubtedly was the reason for the earlier failure.

A further differentiation may be made with regard to the columns of the Metropolis Bridge, Table 1. There is a preponderance of strength when maximum load is considered with reference to yield points for the columns with the flanges turned outward from column axes, over those where the flanges are turned inward. In the former case 11/16-inch web plates and rather slender lattice are used while 1-inch plates and a heavier lattice are used in the latter, the cross sectional areas and lengths being essentially the same. There are three times as many failures occurring above the mean yield point for the first set of columns as there are in the second. Some engineers are of the opinion that a column of small slenderness ratio may be designed very compactly without particular reference to a cross sectional form factor, such, for example, as the radius of gyration of the column section. The tests of the 10 columns for the Metropolis Bridge indicate in this respect that such a factor will enter to some extent, at least so far as this can be differentiated from the effect of yield point variations. In other words, there is apparently an effective distance for placing the material from the column axis when thickness of steel, length and width of columns are considered as major variables. This will be discussed further in connection with the analysis of lattice action:

(*d*) *Maximum Stress as a Function of Slenderness Ratio.*—It may be stated that for the range of slenderness ratios (l/r) existing for the columns of this series several of the best specifications have already taken what amounts to a uniform constant working stress for design. For example, the American Bridge Co. specifications of 1912 takes a safe stress of 13000 pounds per square inch up to values of $\frac{l}{r}=60$ without any correction for the influence of flexure. While the writers are of the opinion that this is very satisfactory practice in design, there is some lack of uniformity in the stress distributions of the columns denoting the presence of flexure. This will be briefly considered for the present in connection with the formula used in the design of the columns of the Metropolis Bridge.

It is stated in the specifications of the Chicago, Burlington & Quincy Railroad that compression stresses are to be reduced by the Rankine formula,[18] $f=p\left[1\pm a\frac{l^2}{r^2}\right]$. This is an empirical formula with a certain rational basis. The maximum stress f consists of two components. The component p arises from the uniform distribution of the maximum load over the column cross section at any point along the axis, as has been discussed. The component $\pm pa\frac{l^2}{r^2}$ is due to a stress couple occasioned by the load acting eccentrically to the column axis, as a result of initial curvatures, imperfect bearings, and other causes which will be discussed more fully later. The constant a is determined experimentally from statistical analyses of tests of columns having different slenderness ratios.

The maximum loads at failure are platted in Fig. 61 after the manner of Buchanan [19] as functions of the slenderness ratio for the 12 members which failed strictly as columns. The different values of the maximum loads correspond to the grades of steel used, the respective zones being shown at the right of figure. Arranging the results with reference to the grades of steel there is no influence discernible here, which can be clearly attributed to that of the reduction factor $p\,a\,\frac{l^2}{r^2}$. While there is a possible reduction as the $\frac{l}{r}$ increases in some cases, there is a rise in others, so that on the whole a constant working stress for columns similar to these may be considered satisfactory.

[18] Burr's Elasticity and Resistance of Materials, 6th ed., p. 467. [19] Engineering News, Dec. 26, 1907, p. 695.

(*e*) *Deflections Analyzed—Eccentricities.*—It is shown in the mechanics of columns as given by Euler [20] that there is a critical length at which flexure will begin. Below this point the member will be subject to pure compression stress when the load is concentric with the column axis. Flexure, for example, occurs in square-ended members at lengths $l \geqq 2\pi\sqrt{\frac{EI}{P}}$ where P is the load and EI is the so-called "flexural rigidity" of the piece, E being the Young's modulus and I the moment of inertia of the cross section. In the columns of the present investigation,[21] where an intentional

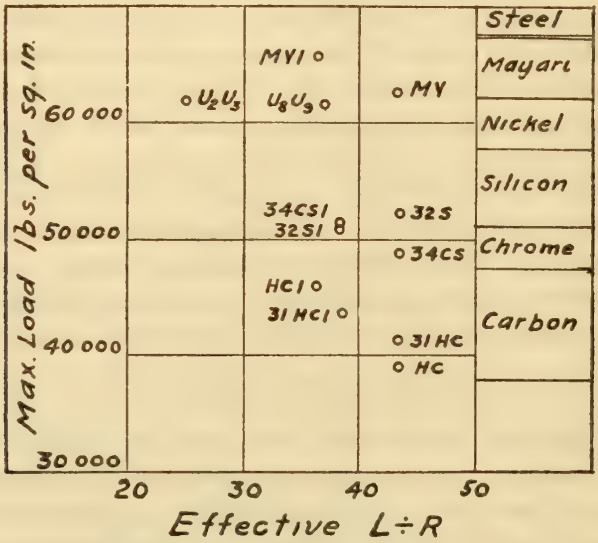


FIG. 61.—*Maximum load as function L÷R*

eccentricity does not exist, such deflections as occur must be due to essential eccentricities in one form or another. These arise as a result of unsymmetric variations in the elastic properties of the material about the centroidal axis, or through displacements of the resultant force from the axis for any reason. The types of eccentricity will be discussed later in the analysis of flexure.

Briefly reviewing the observations for deflection it will be stated that the first intimations of column failure, in the case of the members failing as units, usually occurred in some proximity to the maximum loads, and not exceeding 5000 to 8000 pounds per

[20] See Merriman's Mechanics of Materials for Euler's theory of long columns, 10th ed., p. 192.

[21] The columns US_2MS_1 (carbon and Mayari), and U_2M_1 had cover plates (see Table 1) which were partially "balanced" by flats. These columns, however, had local failures and are exempted in the above remark.

square inch below this load. Scaling was usually the first intimation of proximity to the maximum load. In no case were visible deflections noted below 6000 pounds per square inch from the maximum load. Usually the deflection was not sensible enough to measure, and in any case did not occur with that gradual variation from initial loads which is postulated in the Rankine type of formula. When the deflection was first noticed it increased noticeably in a short range of loadings, as is noted, for example, in column 32S (silicon) (see Table 9); i. e., at 46 000 pounds per square inch there was scaling, but no deflection; at 48 700 there was 3/16 inch deflection observed, with a maximum load at 52 800. For 31HC1 (carbon) (see Table 13) the corresponding values are 34 000 scaling, deflection 1/8 inch at 44 000, and failure at 46 550. For column 34CS1 (chrome) (see Table 15) on the first run to 25 000 no deflection was observable, but at 32 000 of the third run it was found to be but 0.005 inch, and similarly for column LC_0LC_1 (carbon). (See Table 20.) The larger deflections recorded for various columns, while interesting, will not be dwelt upon here as having no bearing on the present analysis of elastic behavior. In view of the "angular" type of failures for the columns U_2U_3 and U_8U_9, the deflections measured (see Table 5), while deserving of study in this connection, are mainly of interest in indicating the character of local phenomena.[22]

(*f*) *Remarks on Deflection Curves.*—An interesting feature is brought out in these tests in connection with the deflection deportment at or near failure. Referring to the 10 columns for the Metropolis Bridge (see Table 1), it can be easily verified that when flexure occurred about the pin there was a point of inflexion (or contraflexure) approximately one-third the length down from the upper square bearing, as is given in the conventional curves of engineering mechanics in connection with the analysis of columns. The deflection curve between this point and the pin takes the flat parabolic form. This may be noted as an example in the view of column 31HC, Fig. 46, while in the machine just after test. On the other hand, when failure occurs in the principal plane longitudinal to the pin, it may be seen that the conventional curve for two square ends was closely realized,

[22] Talbot and Moore remark in their analysis of built-up columns: "The amount of deflection from the original axis for loads up to a point somewhat below incipient failure was found to be slight (generally between 0.04 and 0.1 inch), much smaller than necessary to account for the stresses observed in the columns." Bull. No. 44, Ill. Exp. Sta., p. 51, 1910.

as may be verified by laying a ruler on the column HC_1 of Fig. 50. The character of these deflection curves, considered with the fact that the columns of the Metropolis Bridge failed throughout in smooth curves, indicates that the integrity of action of fabricated steel can be realized in practical column construction to a larger extent than has heretofore been considered possible.

(*g*) *Column Moduli.*—In determining the column mean modulus as given in the upper rows of Fig. 60, the mean strain was found by averaging the four rod readings and dividing by the gauge length of 80 inches. The mean stress is the load divided by the cross-sectional area of the shaft. The ratio of the latter to the former for corresponding values gives a single determination of the modulus, if the values are taken well within the proportional limit. The separate determinations were adjusted by least square methods and the usual formula as follows: There were on an average five separate determinations found from the different stress and strain data within the proportional limit, these being as low as three and sometimes as high as seven, depending on the number of readings. The exact cross-sectional areas were used (see Table 1) for all columns, except U_2U_3 and U_8U_9 of nickel steel, where they were not available, so that the moduli of these columns are omitted in the upper row of Fig. 60. The values for column HC were too few and somewhat discordant, and the modulus for this member was also omitted in the results. The probable error was always taken as two-thirds of the mean error in the following determinations. The values obtained on this basis were:

	Pounds per square inch
Mean modulus of 15 columns	29 600 000
Mean error of modulus	±180 000
Probable error of modulus	±120 000
Mean error of a single observation	±680 000
Probable error of a single observation	±450 000

When the weighted mean was taken, each separate value of modulus being multiplied by the number of observations used in determining it and the total sum being divided by 76, the sum of all the observations, the modulus is again practically as before, 29 500 000 pounds per square inch. The uncorrected average of U_2U_3 and U_8U_9, which were not included in the results of the 15 above, also gives 29 500 000. This value is a fair mean of that for ordinary steel and checks well with other observations on columns

of a size at all commensurate with these.[23] This agreement is believed to show that the testing machine has not an appreciable error in giving loads as recorded, also that there is a good action of the members as a whole with respect to their axial compressions in the testing machines.

(*h*) *Ratio of Lateral Expansion to Longitudinal Compression.*— There are four elastic moduli for isotropic materials, two of which may be considered as independent. These two may be taken in the mechanics of the column as the Young's modulus already found and Poisson's ratio, the latter being the ratio of the lateral expansion of the material to its longitudinal compression. This ratio is of value in estimating the mean lateral strain of the column when under particular loads in lieu of actual measurements. In columns of plain steel there is no stress accompanying this extension, since the column surface is free from stress. Slight stresses doubtless exist, however, in columns of built-up steel. On account of the perturbations experienced from longitudinal diaphragms, column flanges, etc., absolute values of Poisson's ratio can not be found, but the mean more or less qualitative results are sufficient for practical purposes.

Probably the best value of this ratio for the series is obtained by taking the (±) elongation at stations 53 and 54 of the column U_8U_9 (nickel) (see Table 4), the elongation for 54 being divided by the compression under 53 for the various loads within the proportional limit and averaged. In this way the mean value for loads under 30 000 pounds per square inch is found to be 0.291.[24] In the case of eight other sets of readings taken on both alloy and carbon members the mean was found to be, after suitable averaging, 0.327. The value of 0.30 appears to be a fair value for calculation on the built-up co.umn, this being in close agreement with the values often given for ordinary steel, where riveting is not present.

[23] For example, the modulus of column No. 1 of Steubenville Bridge tests, by J. E. Howard, the cross section being 90.7 square inches, the strain average at four corners being taken, was 29 375 000. On columns 2, 3, 5, 29 500 000 was selected by Howard as most representative for the curves taken from the data. (Trans. Am. Soc. C. E., Vol. LXXIII, pp. 435, 443–444.) Talbot and Moore, in their investigation of columns of smaller cross sections and less stiffness than these, remark: "The modulus of elasticity of 28 000 000 * * * checked closely with the total shortening of the columns." (U. of Ill. Exp. Sta., Bull. No. 44, p. 21.) For range of moduli for steel, see Burr's Elas. and Strength of Materials, 6th ed., pp. 274–275. Results range between 28.5 and 29.9 x 10^6 in compression. Also see curves of Buchanan in Eng. News, Dec. 26, 1907, p. 685 (measurements were not made as above), and Johnson's Materials of Construction, 4th ed., p. 510.

[24] In the tests on the Steubenville Bridge columns, by J. E. Howard, Trans. Am. Soc. C. E., 78, p. 429, high carbon steel, this value is given as 1:3.55 (0.282), and this result checked closely with the average of the measured value for the full width of columns. The value of 0.267 from Wertheim is often quoted for plain steel.

2. GENERAL LAWS OF FLEXURE

(*a*) *Primary and Secondary Stresses Discussed.*—It has been stated that flexure in the concentrically loaded column is theoretically impossible within the limits of length as given by Euler. Unsymmetrical stress distributions at the extreme filaments of the cross section of a column indicate the presence of a stress couple which varies along the axis. The line of action of the resultant force on the column deviates from its centroidal axis by a variable amount e, the arm of the couple and the eccentricity of the column. The couple Pe and the eccentricity e were neglected in the earlier discussion of maximum loads and yield points. The stress f at the extreme filaments under the assumed conditions of concentric loading was taken equal to p, the applied stress on the test member. It represented a first approximation to the actual stress distribution in the column. In the theory of structures p is called the primary stress.[25] It is more commonly known as the mean or direct stress.

A second approximation to the actual stress system is obtained when the stress resulting from the presence of the couple is added to the mean stress p. The stress difference $f-p$, denoting flexure, is known as the secondary stress.[25] It will be called the bending stress in the following discussion. The bending stress at a point in the column cross section varies directly with its distance from the centroidal axis, according to the law of the beam. It has its greatest and least values at the extreme filaments of any cross section at a point on the axis of the column where the stress couple is a maximum. The analytical expression for the bending stress is $f-p=\frac{Pec}{I}=\frac{pec}{r^2}$, where c represents the distance from the column axis to the extreme filament of the cross section, I the moment of inertia of the section, and r its radius of gyration. The average stress at the extreme filaments is found in terms of the observed compressions given in the tables by the relation $f=E\frac{g}{l}$, where g is the compression, l is the gauge length of the extensometer, and E is the modulus of elasticity. Similarly $p=E\frac{g_o}{l}$, where g_o is the calculated compression on the axis determined by taking the average of the four compressions g at the extreme filaments.

[25] Johnson, Bryan, and Turneaure, Modern Framed Structures, 9th ed., 1916, Pt. II, p. 500.

Since the law of variation of $g - g_o$ and g_o is known from the tests and c and r are constants for a particular column, it is important as the basis of further discussion to consider how the eccentricity varies as the load increases. The principle of superposition of small strains in mechanics permits component stresses, strains, couples, and eccentricities to be considered separately in this discussion. The component functions may be added algebraically in obtaining the resultant. Certain restrictions which are to be considered will be given later.

(*b*) *General Types of Eccentricity.*—There are two general types of eccentricity to be considered in the theory of columns. The first type includes all eccentricities which are inherent in the columns in its unstrained state. They may be present either as the result of initial curvature introduced in the column during fabrication or as the result of variations in the elastic properties of the different steel shapes. An actual eccentricity of this type also may be introduced in conformity with the column design. While the inherent or initial eccentricity may vary along the column axis, it remains constant by definition at a particular point as the load on the column increases. Therefore, the portion of the bending stress $f-p$ due to this eccentricity is proportional to p alone.

The second type of eccentricity to be considered is that which is introduced in the straining of the column. The line of action of the resultant force is in general displaced from its original position at the initial load as different increments of load are applied. The effect is to modify the curve of initial eccentricity for the column. The increment ($\pm$) to the curve of initial eccentricity may occur in a number of ways: (1) When the terminal initial eccentricities are maintained constant, as in the case of a column with restrained ends, the centroidal axis is displaced laterally a variable amount $y = f(x)$. This is known to designers as the secondary flexure. (2) There may be rotations of the column at the ends due to imperfect end bearings, relative slipping of pin plates, or the overcoming of the pin friction. (3) The integrity of action of the different shapes is in general not conserved. The stress and strain functions or their derivatives are subject to finite discontinuities at certain periods of the loading as a result of the laminated character of the built-up steel, the slipping of pin plates, the irregular action of lattice bars, and transverse diaphragms, the effects of initial strain of fabrication.

It is the purpose to determine from the test data as far as is practicable the relative weight of influence of the different factors

which modify the curve of initial eccentricity. The theoretical law of variation of the maximum stresses in an ideal column of known initial eccentricity will first be treated as the norm or

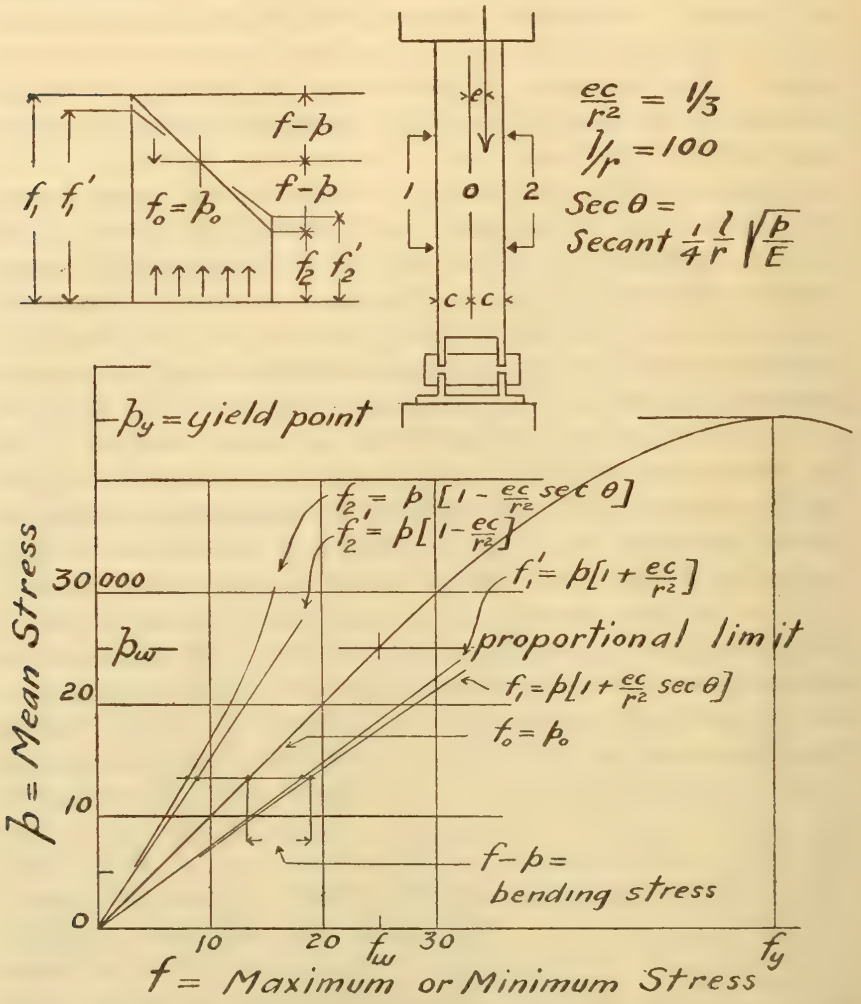


FIG. 62.—*Normal stress distribution in the ideal column with square ends by the laws* $f=p\left[1\pm\frac{ec}{r^2}\sec\frac{1}{4}\frac{l}{r}\sqrt{\frac{p}{E}}\right]$, $f=p\left[1\pm\frac{ec}{r^2}\right]$ *and* $f=p$

standard of comparison. The departures of the test columns from this ideal case will be discussed later in the text.

(*c*) *Law of Stress Distribution for the Ideal Case.*—The column shown diagramatically in Fig. 62 is supposed to be perfectly elastic and continuous in structure within the interval of working

stress $o<f<f_w$, $o<p<p_w$. It is assumed to have a uniform square bearing at the upper end and a pin bearing at the lower end. Since no deflection was observed in the interval of working stress, the column will be considered for the purpose at hand to be perfectly restrained at the ends in this interval. The average slenderness ratio of the test columns is 30, the maximum value being 44. The value of $\frac{l}{r}=100$ has been used in drawing the following curves. The mean value of the initial eccentric ratio $\frac{ec}{r^2}$ is taken as 1/3, this being the approximate average initial ratio for the test columns. The applied stress p is given in increments of 10 000 pounds per square inch. The relation between the stress f at the outer filament at mid length and the applied stress p is given by the expression[26] $f=p\left[1\pm\frac{ec}{r^2}\ sec\ \frac{1}{4}\frac{l}{r}\sqrt{\frac{p}{E}}\right]$, this formula being correct within the limitations of the ordinary law for the beam. The term secant $\frac{1}{4}\frac{l}{r}\sqrt{\frac{p}{E}}$ is found from a table of radians. The formula $f=p[1\pm\frac{ec}{r^2}]$ may be used for small values of $\frac{l}{r}$ and has been platted in Fig. 62. When there is no eccentricity $f=p$, the law for the concentrically loaded column holds.

The method of platting to be described is simply an extension of the ordinary method of platting stress-strain curves. The applied stress p is taken as the ordinate, the calculated stress f is taken as the abscissa. The measured deformation g at the outer filament in the test member was previously shown to be proportional to f. The average g_o of the measured values g is the mean compression at the column axis. The curve $f_o=p_o$ is the ordinary stress-strain curve whose slope represents the modulus of the column when f_o is taken in appropriate units. This is drawn in the figure with a slope of 45°.

The bending stress $f-p$ in the case of this ideal column hypothecated for the purpose of the discussion is seen on the diagram of Fig. 62 to increase in almost direct proportion with the applied stress p within the proportional limit of the column which has also been taken to be the upper limit of the working stress f_w, p_w. For the purposes of a practical discussion the p, f curves may be assumed to diverge radially from the origin, minor curvatures

[26] Johnson, Bryan, and Turneaure, Modern Framed Structures, 9th ed., Pt. III, 1916, p. 38.

being neglected, under the premises defined. The working limit f_w, p_w in engineering practice is commonly given by a column formula which shows implicitly how f_w, p_w varies with the $\frac{l}{r}$ or other form factors as has been illustrated in the case of the Rankine formula. For a particular column, however, where the latter are held constant, the linear law $f \propto p$; $o < f < f_w$, $o < p < p_w$, may be assumed to hold in all cases, within the domains $o < \frac{l}{r} < 80$ or even 100, and $o < \frac{ec}{r^2} < \frac{1}{3}$. The deviation from linearity is somewhat greater in the case of pivoted columns but is never large in the columns of engineering practice.

(*d*) *Method of Calculation of Maximum Stresses.*—The law of the distribution of maximum stresses in the columns to a second order of approximation will now be discussed in the light of the preceding remarks. A portion of the observed compression data of column 32S (see Table 9) is first reproduced in the following Table 22 for the purpose of illustrating the method of calculation of the maximum stress from the data. The actual laws of variation of the stresses f and $f-p$ will then be shown graphically for a number of the test columns in order to direct attention to the typical stress phenomena which are found for the whole series of columns.

TABLE 22.—Illustrating the Calculation of Stresses f and $f-p$ at Station 1 of Column 32S

(a) Applied load, pounds per square inch	(b) Axial compression, mean of stations 1–4 g_o	(c) Axial stress $=(b)\times\frac{E}{80}$ p	(d) Compression at station 1 g	(e) Stress at station 1 $=(d)\times\frac{E}{80}$ f	(f) Bending stress at station 1 $=(e)-(c)$ $f-p$	(g) $(f-p)\propto p$ as in normal case of Fig. 62
1000	0	0	0	0	0	0
5000	0.0105	3890	0.0065	2400	1490	1500
17 000	.0422	15 600	.0380	14 100	1500	6000
21 000	.0526	19 400	.0480	17 800	1600	7500
25 000	.0644	23 800	.0592	21 800	2000	9000

The increments of applied loads under the heading (*a*) are given in multiples of 4000 pounds per square inch, beginning with 1000 pounds per square inch as the assumed point of zero strain.

The heading (*b*) gives the mean compression g_o on the axis at a particular load and is found by averaging the compressions given for stations 1 to 4 in Table 9. The corresponding axial strain is determined by dividing the mean compression under (*b*) by the gauge length of the extensometer. The axial stress under heading

(*c*) is determined by multiplying the mean strain of (*b*) by the mean modulus E, here taken as 29 600 000 pounds per square inch as was previously calculated. Similarly, the compression observed at station 1 for the outer filament is recorded under (*d*). When the quantity (*d*) is multiplied by 29 600 000 and divided by 80 the fiber stress f is determined as is given under (*e*). The difference between the values for (*e*) and (*c*) gives $f-p$, the bending stress as recorded under (*f*). The last heading (*g*) shows the ideal variation of the stress f at station 1, in accordance with the law of proportionality of stress holding for a prism or column of small slenderness ratio and constant eccentricity as has been given but which is not assumed to hold for the test columns.

It may be seen by reference to the above table that if the initial load is added to items (*c*) the results correspond closely with 1000, 5000, 17 000, etc., the loads applied on the testing machine as given under (*a*). The slight discrepancies between the two sets of values are due to the fact that small variations occur in the modulus when it is calculated from particular loads and compressions, intermediate values contributing to the mean being here omitted. The bending stress under (*f*), viz, $f-p$ for 25 000 pounds per square inch, should be approximately six times the amount found for 5000 pounds per square inch if the law of proportionality holds in column 32S. Further data will be submitted before discussing these discrepancies.

(*e*) *Variations of Stress Shown Graphically.*—A complete set of stress-strain curves is shown to an enlarged scale on Figs. 63 and 64 for columns MY, HC, 32S, 34CS, LC_0LC_1, US_2MS_1, and U_2M_1.

These columns are selected for the purpose of illustrating the characteristic types of curves which occur in the larger series. The observed mean stress p found from the testing machine is platted as the ordinate of each curve as was done in Fig. 62. The observed compressions g in 80 inches for the extreme filaments at the mid lengths of column are platted as the abscissas of the curves. (See data of Tables 6, 7, 9, 10, 16, 18, and 20.) These abscissas are proportional to the mean stresses f at the respective stations when the modulus of the column is considered a constant. The average curve is also platted as has been done elsewhere for all the columns, its abscissa being g_0. The distance $g-g_0$ along a particular abscissa between the average curve and the curve corresponding to a given station is proportional to the bending stress $f-p$ at the station. It will be seen that $g-g_0$ as a rule is constant

above a critical value of mean stress, $p_c = 5000$ pounds per square inch, as was already found analytically in the case of column 32S. In other words, the curves are generally equidistant above the ordinate p_c. This general parallelism of the curves is characteristic of the whole series of columns. There is, however, a diver-

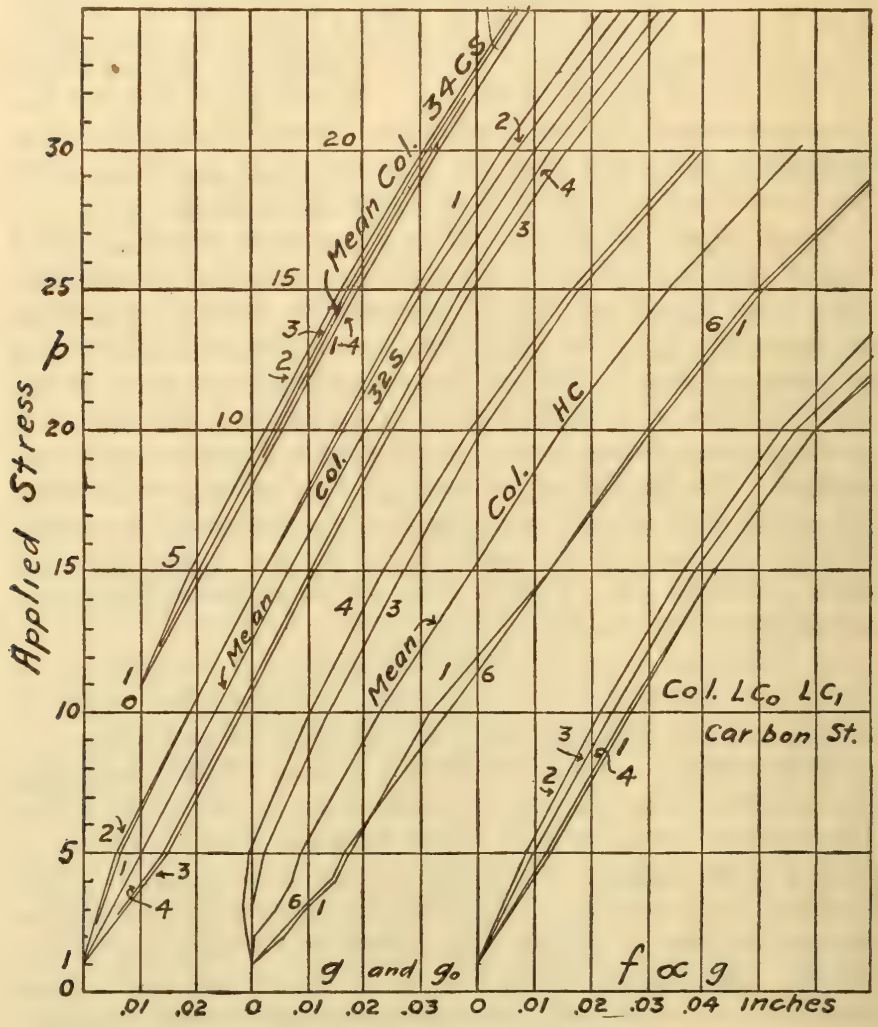


FIG. 63.—*Typical stress deformation curves*

gence instead of a parallelism of curves in the case of column US_2–MS_1 (carbon). Enough observations were taken in the case of columns HC and MY to show definitely that there is practically a radial divergence of the curves below the critical value p_c; in other words, neglecting minor departures and curvatures, the stress f is

a linear function of p for low loads. The law for the larger number of columns of the series may therefore be stated analytically to a reasonable degree of approximation:

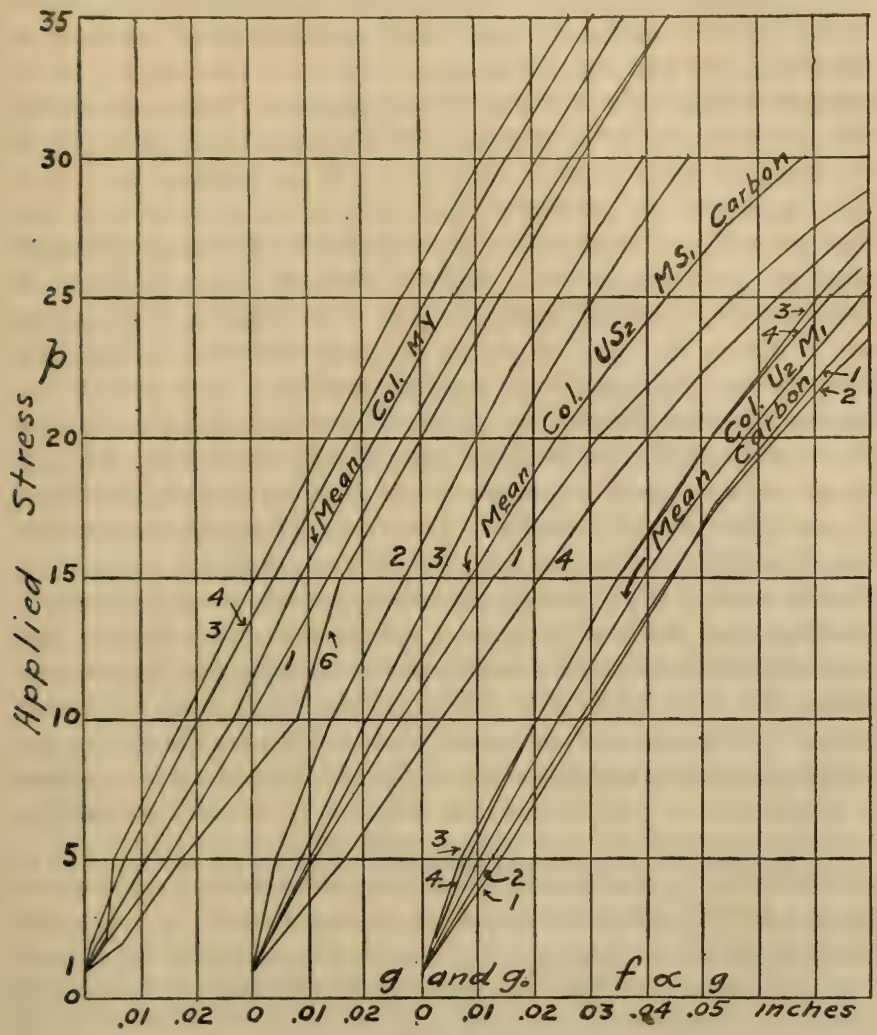


FIG. 64.—*Typical stress deformation curves*

$$f-p = (g-g_0)\frac{E}{80} = \pm p\frac{ec}{r^2} \text{ in the interval } o<f<f_c,\ o<p<p_c$$

$f-p$ = a constant in the interval $f_c<f<f_w$, $p_c<p<p_w$.

In the above expressions f_c, p_c denote the stresses at the points of discontinuity in the slopes of the curves, and f_w, p_w denote the limits of safe working stresses. The parallelism of curves was

found in most cases to hold with little variation up to the stresses f_y, p_y at the mean yield point of the steel.

The nearly uniform divergence of the p, g curves below the stress $p_c = 5000$ pounds per square inch denotes that the eccentricity of the columns is maintained approximately constant in the interval. The mean stress p_c at which the rate of divergence changes and the curves become either parallel or diverge at a different rate indicates, in the opinion of the authors, the point at which the built-up steel ceases to act as a unit in resisting the stress. The slipping of the pin plates of the columns is believed to be the main factor in producing the discontinuity in the curves although slipping about the pin may have contributed when the plane of flexure was perpendicular to the pin. The slipping of pin plates was noted in the case of all the columns upon which pin-plate observations were made at loads as low as 10 000 pounds per square inch of shaft section. There is strong evidence in the case of column 31HC that the large interior pin plates next the continuous webs slipped as a whole at a load as low as 5000 pounds per square inch of shaft section. The observations were extended nearly as high as the quarter point of the columns in some cases. If wide areas of close riveting are inadequate to prevent slipping at relatively low working stresses, it is logical to presume that slipping may have occurred at other points between the shapes composing the shaft where the riveting is less dense than at the pin plates.[27] The relative movement observed is never large but the stress phenomena and behavior of the pin plates lead the authors to believe that it may at times be sufficient in amount to cause the

[27] The total shearing force along the plane of contact between two shapes at a particular point in the built-up column is given in the mechanics of materials (Merriman's Mechanics of Materials, 10 ed., p. 270) by the relation $F=\frac{\Delta M}{I}\int_y^{y_1} zydy$ where ΔM is the increment of the bending moment in the distance Δx along the column, I is the moment of inertia, z is the width of the shape or lamina, y is the distance to the surface in question and $y_1=c$ is the distance to the extreme filament of the column cross section. If F has an upper limit, F_1, the frictional resistance of the contiguous shapes against relative sliding, the column will act as a unit so long as the shear at any point does not exceed the limit F_1. When this limit is exceeded in a particular region, sliding will occur along some contact plane at which the shear is F_1. The divided portions no longer act in unison. The sliding action becomes progressive as other contact surfaces experience the shear F_1. The slopes $\frac{dp}{df}$ of the stress strain curves become discontinuous. The general effects on the curves is illustrated conceptually in Fig. 65(f). The stress strain curves of columns MY and HC show evidences of this behavior in the interval of loading $o<p<p_o=5000$ *pounds* per square inch. (See Figs. 63 and 64.) The action is probably here confined to the pin plates. It is the opinion of the authors that generally wherever the stress strain curves show abrupt changes in curvatures above the mean stress $p_o=5000$ pounds per square inch this slight relative sliding may be taking place at the point in question. The behavior of the stress strain curves of column HC, Fig. 63, may be cited as an instance. The pronounced changed in curvature in column MY at 10 000 pounds per square inch probably denotes an error in reading. The "murmurs" which may be heard in the straining of the built-up columns, and which do not occur in tests of rolled sections, when they are not directly traceable to the behavior of lattice bars and transverse diaphragms, may be attributed to such actions as have been described.

stress and other functions to experience finite discontinuities along the surfaces of contact of the different shapes. Such surfaces of contact are treated in the general theory of elasticity as surfaces of limited stability.[28] It may be noticed that the average curves as given to an enlarged scale in Figs. 63 and 64 have somewhat larger curvatures than are commonly found for rolled sections tested as columns, the stress-strain curves of the latter being nearly straight lines within the intervals of working stress. This is a further indication in the opinion of the writers that there is not perfect integrity of action of the shapes. The extent to which the continuity of structure of built-up steel is conserved during straining is discussed further in connection with the subjects of initial strain and the behavior of lattice, diaphragms, pin plates, and other details.

(*f*) *Components of Eccentricity Discussed.*—In placing a column in the testing machine it was balanced under its own weight on the pin and bolster after these had been accurately centered on the lower platform. It may be assumed for all practical purposes that there was no play or lost motion at the pin, and that the axes of the member and the testing machine intersect at the pin. A nearly uniform contact at the upper head of the testing machine was secured by oscillating the lower or adjustable head until the planes of the upper face of column and the testing machine head were brought into parallelism. This was determined by suitable measurements at the outer corners of the upper face of the column. The initial load of 1000 pounds per square inch was then applied.

The components of the eccentricity e in a column in its initial state of strain before slipping of plates occurs are as follows (see Fig. 65): (1) There is a component e_1 from initial curvature induced during fabrication. (2) There is a component e_2 due to slight variations in Young's modulus of the different shapes. This is theoretically determined by the formula $e_2 = \sum \frac{p_i a_i d_i}{p_i a_i} = \sum \frac{E_i a_i d_i}{E_i a_i}$ where $p_i = p_1, p_2 \ldots$ represents the stresses in the respective shapes, $a_i = a_1, a_2 \ldots$ are their areas, $d_i = d_1, d_2 \ldots$ are their distances from the column axis and $E_i = E_1, E_2 \ldots$ are the corresponding moduli. An actual determination of this component requires that each modulus E_i be definitely known together with its orientation

[28] Talbot and Moore have called attention in their tests of riveted joints to the fact that the paint used in the assembly has some influence in determining the yield stress at which slipping occurs. (Ill. Eng. Exp. Station, Bull. 49, p. 47.)

with respect to the column axis. (3) There is a component e due to the fact that perfect parallelism of the planes of upper

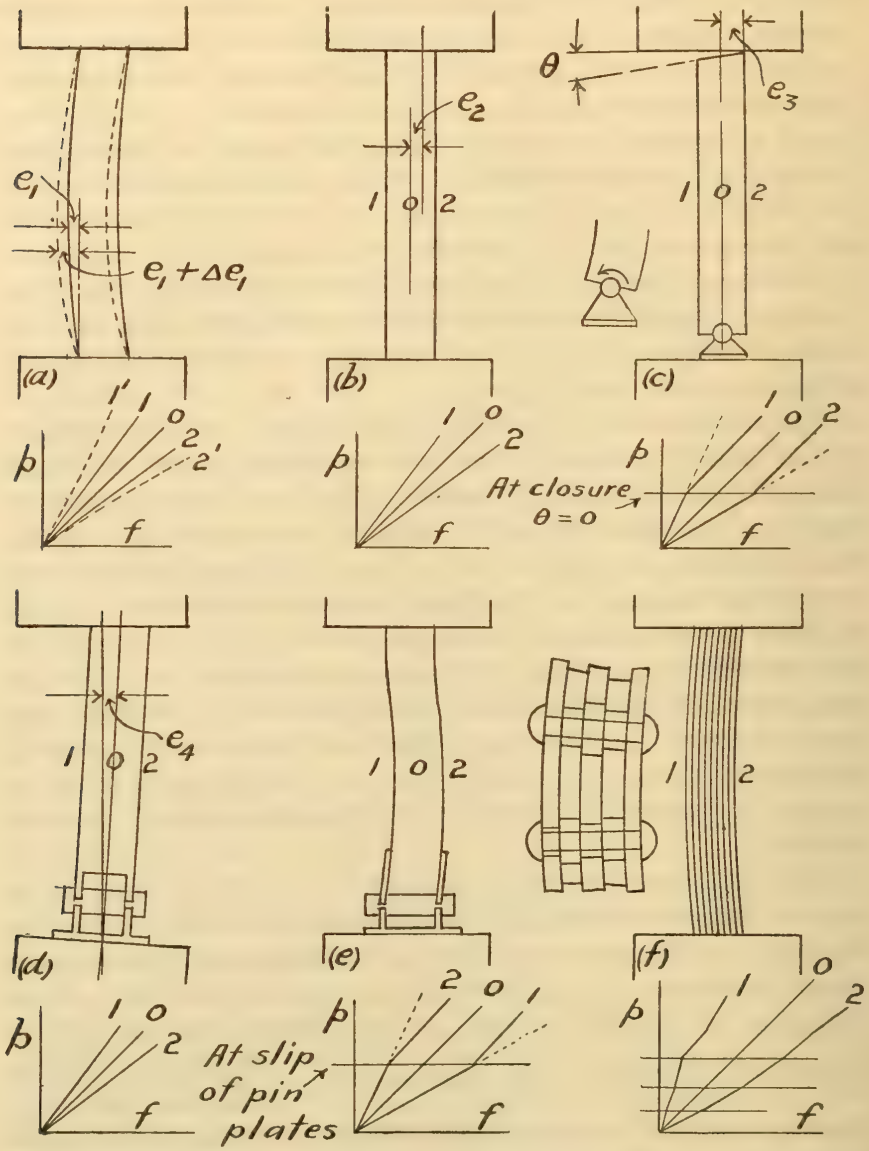


FIG. 65.—*Showing types of eccentricity present in the columns tested and the character of the corresponding stress strain (p, f) curves as a result of (a) initial curvature, (b) variations in component moduli, (c) imperfect bearing at upper head, rotation on pin, (d) angular deviation of axis of column from axis of testing machine, (e) slips from pin plates, (f) laminated structure*

face of column and head of the testing machine is unattainable. The planes will differ in general by a small angular amount θ.

There will be under these conditions either one, two, or three point contacts on the upper head, the three or higher point contact denoting parallelism of planes, in which case $\theta = o$, and e_3 vanishes. (4) There is a component e_4 due to the fact that even when parallelism is attained the axis of the column is not in general truly normal to the planes of upper and lower heads of the testing machine. It will intersect the planes of the lower and upper heads at a small angle with the axis of the testing machine.

The component e_1 from initial curvature may be neglected in comparison with the others. The component e_2 on account of the relative constancy of the modulus is doubtless initially small, but may increase if there is not perfect integrity of action of the different shapes in resisting the applied load. It is impossible to obtain e_2 from the data available to the experimenters. The components e_3 and e_4 can not be quantitatively differentiated with any degree of accuracy. It is only practicable to consider the total eccentricity e, and this may be determined for any particular column by the formula $e = \frac{f-p}{p}\frac{r^2}{c} = \frac{g-g_0}{g^0}\frac{r^2}{c}$ where g and g_0 represent the compressions at the outer filaments and centroid of the column cross section, respectively. The mean total eccentricities at the, mid lengths for the columns given in Figs. 63 and 64 are calculated by means of the above equation at various loads, and are shown in Table 23 below.

TABLE 23.—Mean Eccentricities in Inches at Mid Lengths, Calculated by the Formula $e = \frac{g-g_0}{g_0}\frac{r^2}{c}$ for Seven Columns at Different Loads p in Pounds per Square Inch

Loads in pounds per square inch	Column						
	34CS	32S	HC	LC_0–LC (carbon)	MY	US_2–MS_1 (carbon)	U_2M_1
5000	0.35	2.94	3.60	0.71	1.79	1.66	1.71
10 000	.18	1.38	1.90	.36	1.13	1.25	.94
20 000	.10	.60	1.10	.17	.50	1.00	.56
30 000	.09	.40	.74	.09	.35	1.24	.63
Values of $\frac{r^2}{c}$	4.03	7.34	4.03	4.28	4.02	4.82	5.67

According to the above equation, e is inversely proportional to p in the case of the columns where $f-p$ is constant. It is nearly constant above $p = 10\,000$ pounds per square inch in the case of column US_2MS_1 (carbon), where there is some divergence of the p, g curves. In the case of column HC the eccentricities at loads

of 2000, 3000, 4000, and 5000 pounds per square inch are 4.93, 4.54, 3.86, and 3.60, respectively. If there were a true radial divergence of the curves in the interval $o < p < p_c = 5000$ pounds per square inch, the theoretical considerations previously discussed show that the eccentricity would be maintained constant in the interval. The gradual decrease shows that there is some slipping occurring in the interval below 5000 pounds per square inch. The authors are of the opinion that the initial eccentricity is principally introduced at the upper head, and that the inherent eccentricities in the columns are small in all cases.

A suggestion to the authors by H. S. Prichard is interesting in showing qualitatively how the discontinuity in slopes of the p, g curves may occur in an ideal case, although the calculated stresses f and $f-p$ are several times larger than the values determined from the observed data. Let a column be considered first to act as a rolled section without discontinuities in the functions. Assume the angle θ (Fig. 65(*c*)) between the planes of upper face and head is small, but of finite amount. Let the component of eccentricity as a result of point or line contact be e_3 as previously given. The analytical relation for the bending stress under a load P_1, which does not exceed the critical value $P_c = A p_c$, is:

$$(1) \qquad f_1 - p_1 = \pm \frac{P_1 e_3 c}{I} = \pm \frac{p_1 e_3^2}{r^2}: \; o < f_1 < f_c, \; o < p_1 < p_c.$$

The column is subject to slight curvature under strain, so that θ eventually becomes zero, and the planes at the upper head have parallelism when the critical stress p_c is reached. The stress relation becomes (2) $f_c - p_c = \pm \frac{p_c e_3^2}{r^2}$ at this point. The eccentricity e_3 vanishes. Any further increment of stress (3) $f_2 = p_2$, is uniformly distributed over the column cross section, p_c still acting to maintain closure of the joint at the upper head. Adding (2) and (3) there results (4) $f_c + f_2 =$ resultant maximum stress $f = p_c + p_2 \pm \frac{p_c e_3^2}{r^2}$ $= p \pm \frac{p_c e_3^2}{r^2}$. In other words, f is equal to the mean stress plus or minus a constant bending stress $\frac{\pm p_c e_3^2}{r^2}$ as is shown generally in Figs. 63 and 64 for the p, g curves above the mean stress p_c.

It is quite probable that a somewhat similar behavior, but in inverse order, is occurring in the actual test columns at the pin end

from an unequal and limited slippage of the pin plates. The column is subject to some slight initial eccentricity, as has been shown. The end is practically restrained to perpendicularity with the lower head up to the point of main slipping at p_o, when the end tangent to the strained axis deviates an amount θ from the original unstrained position as is indicated in Fig. 65 (e). The plates and perhaps other shapes slip relatively; f and p receive uniform increments of stress and the rate of slipping is approximately proportional to the mean stress, neglecting minor variations. The slipping appears to operate as an easement to the stress. For if the eccentricity remained constant throughout the test, the formula $f = p \pm \frac{pec}{r^2}$ shows that f is proportional to p and there would be a divergence instead of a parallelism of the p, g curves, and correspondingly higher stresses f and $f - p$ somewhat after the manner as is indicated for column US_2MS_1 (carbon), Fig. 64.

The divergence of the p, g curves in the case of column US_2MS_1 (carbon), in the opinion of the authors is explained by the fact that the column consists of two component struts joined by the battens and intermediate ties. (See Fig. 56.) One of these struts appears to have received a greater proportion of the load than the other in bringing the upper head to bear on the column. The load on the column is delivered eccentrically as a result, and the eccentricity remains fairly constant after a load of 10 000 pounds per square inch is reached.

In this discussion the point or line contact was taken for the purpose of analysis at the outer periphery of the upper face of the column. The amount of actual bending stress indicates that the initial eccentricity is not as large as will be found upon the above assumption. It is probably more reasonable to assume in the light of actual stress distributions that generally the upper surface has an imperceptible curvature or waviness and that the load is applied on a high spot with less eccentricity than the amount c, as appears to have been the case with all the columns. (See Table 23.) The analysis is similar to the preceding. The important distinction the authors wish to make is that the initial eccentricity at the pin is nearly zero from the manner of setting the columns in the testing machine. The unequal rates of slipping of the pin plates are caused by the stress couple, and are also probably influenced by different degrees of resistance of the riveted surfaces. The force on the columns, in the opinion of the

authors, is applied eccentrically not as a result of inherent or primary eccentricities in the columns, at least to any extent, but rather as a result of the initial eccentricity at the upper surface of contact, this depending on the degree to which a perfect bearing was obtained.

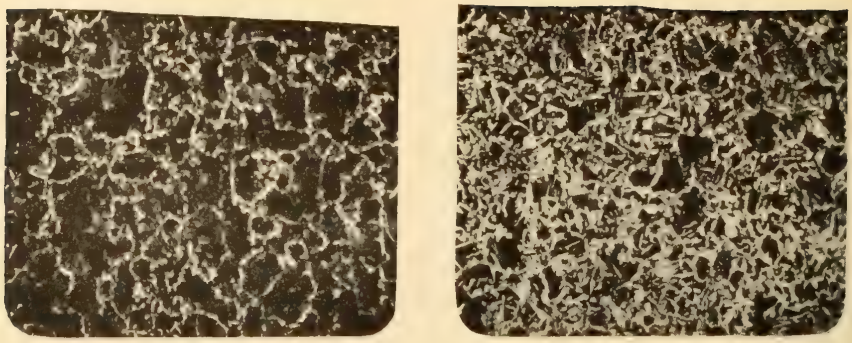
3. INITIAL STRAIN IN BUILT-UP COLUMNS

When stress-strain curves are platted from the data found on two ordinary test specimens of plain steel of appropriate lengths, one being tested in tension and the other in compression, it has been found that the slopes of the curves are in practical agreement at the same stresses up to the yield point of the material. After this point is reached the curve in tension takes the usual form up to the strength of the material. The maximum ordinate of the compression curve is, however, in any case scarcely greater than the yield point of the steel.[29] In the case of the built-up columns here considered it has been shown on the contrary by the tests that the proportional limit is only about half the yield stress of its component steel. This is in substantial agreement with the type of stress-strain curves usually found for large columns. Evidence will be given to support the theory that the low proportional limit is principally due to two causes. One is the presence of initial strains in the columns occurring from fabrication and chiefly from riveting; the other appears to be incidental to the physical constitution of the fabricated steel itself, as a result of bending strains induced by initial curvatures in the component shapes from the clamping action of riveters.

(*a*) *Initial Strains from Punching and Riveting.*—The important initial strains, apart from those introduced by straightening of shapes, are commonly considered to be caused by the process of punching and riveting and clamping actions of rivets. The experiments of Barba[30] on steel plates (French) had previously appeared to establish the fact that the effect of punching in deforming the material is confined to a region within a millimeter of the sheared edge, which in the ordinary process of subpunching 1/16 inch less and reaming to 1/16 inch more than the nominal diameter of rivet would undoubtedly remove. It has recently been remarked

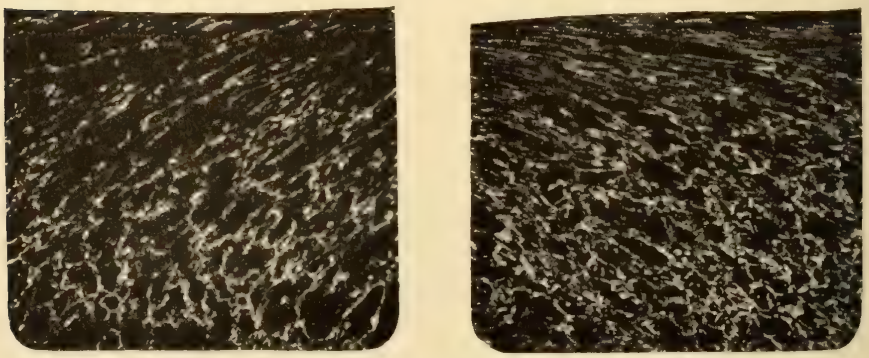
[29] See, for example, numerous such curves platted by Johnson from reports of Watertown Arsenals; "Materials of Construction," 4th ed. (1901), p. 490 et seq.; also parallel values of elastic limits for tension and compression, Burr's Elas. and Resist. of Materials, 6th ed., p. 274; and Rickett's paper, Trans. Am. Soc. of Civ. Engrs., 1887.

[30] Burr gives results of Barba in "Elasticity and Resistance of Materials," 6th ed., p. 324.



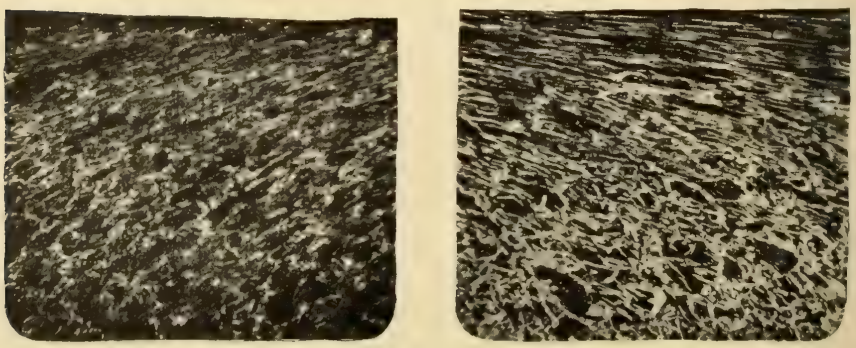
Mayari steel Carbon steel

FIG. 66.—*Drilled sections of steels magnified 67 diameters. The upper edges are the parts directly adjacent to the drill. The microstructure shows no visible distortion present*



Mayari steel Carbon steel

FIG. 67.—*Punched sections of steels magnified 67 diameters. The upper edges are the portions most severely "worked" from the shearing action of the punch*



Mayari steel Carbon steel

FIG. 68.—*Riveted sections of steels magnified 67 diameters. The upper edges are adjacent to the rivets and show the combined effects of "working" from punch and rivet*

by J. E. Howard [31] that reaming commonly does not remove all the material that is disturbed by the operation of punching. It seemed advisable under the conditions of modern manufacture and workmanship to briefly examine this point again. Two plates 5 by ⅜ inch of high carbon and Mayari steel, respectively, were tested. A double row of punched, riveted, and drilled holes of ½ inch diameter were placed in series in the plates. There were two holes of each set spaced 2 inches apart, the rows being 2½ inches apart. The material was planed in a shaper until the midsection of one row of rivets and holes was exposed. Etchings were made by the metallurgical division of the Bureau of Standards on polished sections taken through the rivets and holes and magnified to 67 diameters. (See Figs. 66, 67, and 68.) The thicknesses of distorted regions as measured are given below. They may be assumed to apply practically to the other steels without material error.

Sample	Mechanical treatment	Radial thickness of distorted area
		Inch
Carbon	Riveted	0.031
	Punched	.024
	Drilled	Not enough to measure.
Mayari	Riveted	027
	Punched	028
	Drilled	Not enough to measure.

The evidence submitted warrants the inference that the usual practice of reaming ⅛ inch is quite ample to remove all sensibly distorted material,[32] and it is difficult to conceive of the existence of internal stresses in absence of a restraining force on the periphery of the holes.[33] The field of action is too close to the machined surface. There is no outer ring of stressed material to maintain the stresses in the absence of the rivet pressure.[34] Further evi-

[31] Trans. Am. Soc. of Civ. Engrs., 73, p. 445; Trans. A. S. C. E., 63, p. 101. Waddell.

[32] Burr's Elas. and Resist. of Materials, 6th ed., pp. 317–318.

[33] That is of the order of magnitude here considered and involving values which would have an effect on the elastic limit. There are undoubtedly elastic sets which tend to vanish in time.

[34] A rigorous distinction should be made as to what constitutes initial strain in steel, as very imperfect notions seem to be entertained commonly in this respect. A beam from the rolls after cooling will sometimes fracture its entire length of web with a loud report when a tool first enters same. Similarly, an ingot partly sawed through longitudinally will burst apart violently at the remaining portion and with a measurable deflection visible in the pieces. This strain is then somewhat comparable to that stored up in a Rupert drop and is obviously a proper initial strain in the pieces. On the other hand, the mere cold working of pieces, as in straightening shapes by straining beyond the yield point in "fiddles," rolls, and "gag presses" may or may not introduce initial strains proper, except as strains are entrained in the parts, through the manipulation, which are less than the yield point of the steel. What the designer obviously desires is that there shall be no resultant strain occur from the ensemble of stresses in the column and in

dence will now be adduced to sustain the opinion of Howard that the chief internal strain occurs from the rivet itself. The driving introduces a radial compression, theoretical considerations will show, which falls off inversely with the distance from the face of the rivet, together with conjugate circumferential compressions in the ring elements around the rivets. The clamping power of the riveters, which is large, in compressing the plates, the contractile force of the rivet in cooling, and some annealing action of cooling rivets undoubtedly complicate the situation. The rivets in a number of cases during the experiments at a point of loading well advanced parted with their heads with sharp reports, showing the tendency of the plates to expand outwardly with increase of crimping, the contractile force of rivets resisting this action. Considering the essentially radial character of the stress, whatever the resultant action of the composite effects may be, there are effective components according to Howard which in so far as a free stress exists and the material has not been permanently strained, unite with the direct stress from loading. The result is that the rate of increase of strain becomes variable at a considerably lower point than would be found in the independent results on a test piece. The action would be much the same in many respects as if at the beginning of the column test an initial load had been placed upon the test member unbeknown to the observer and the weighing beam had been then rebalanced at zero. In the course of the experiments the observer would get an unexpected lowering of results under the normal values due to the initial load. In the type of initial stresses under consideration, however, while the proportional limit is lowered, the columns still fail at the yield points as was shown. This is believed to be explained by the fact that the flow is not uniformly distributed through the column, but occurs in regions locally around each rivet. New regional equilibriums very probably occur as a result of compressive density changes, so that while the rate of

proximity to the yield point which might cause the material to flow under working conditions. Analytically, the criterion to be applied in the case of a member free from surface stresses is that the differential equations for stress on an internal volume element, viz, $\frac{\partial X_x}{\partial x}+\frac{\partial X_y}{\partial y}+\frac{\partial X_z}{\partial z}=o$ and two others shall have $X_x=X_y=X_z=o$, etc, for a solution. (See Burr's Elas. and Resist. of Materials, pp. 877–880.) In general, however, it will be found that this is otherwise on account of the presence of initial stresses, which do not affect the static equilibrium of the body under external forces. The method of selecting arbitrary functions which may be so adjusted that the solutions obtained for X_x * * * shall be compatible with external boundary surfaces free from stress, has been suggested and illustrated by Love, Art. Elasticity Encyc. Brit., 11th ed., **9**, p. 160. For practical experimental methods suggested for determining such strains, see Marburg, Pro. Am. Soc. Testing Materials, **9**, p. 386.

strain is increasing above the proportional limit the column load still ultimately reaches the mean yield point of the component steel. There is a tendency shown, moreover, in test pieces to hold the load at constant stress with increasing strain after the yield point is reached. The tendency for the load to be kept up to a maximum also appears the more probable in riveted steel in that the contractile power in each rivet acts to cause constraints like a tie on the otherwise free surface of the column. This undoubtedly has some restraining action to maintain load at the yield point of the steel, even if the pressure from the rivet heads is not continuously distributed over the column face.

(*b*) *Tests to Show the Effect of Riveting on the Proportional Limit.*—Four tests were made on 10-inch I beams (40 pounds per foot) 4 feet 6 inches long. The specimens had small slenderness ratios so that they might fail near the yield points in compression without any appreciable reduction factor through column flexures, and no plates were riveted to the beams. For the two plain beams the maximum loads were 26 750 and 28 700 pounds per square inch, respectively, with a mean of 27 730, scaling occurring at 25 000. The yield point from separate tensile tests was found to be 31 410. Six sets of extensometer readings were taken at the mid lengths on the points of flanges and center line of web. No deviation occurred from the initial tangent of the stress-strain curves, until 21 000 to 22 000 pounds per square inch was reached. In the two other beams, two rows of ¾-inch rivets in punched and reamed holes were driven in the flanges and three rows in the web, and similar readings taken as before. The maximum stresses were found to be 29 450 and 30 000 pounds per square inch, respectively, with a mean of 29 730 pounds per square inch, the tensile yield point as independently determined being 32 800 pounds per square inch. The deviations from the right line of stress-strain curves in each case was 6000 to 7000 pounds per square inch lower than the corresponding values for the first case. The lowest values occurred for those readings which were directly over the line of rivets on the center line of the web of the 10-inch beam. Since no plates were riveted on these beams to cause a possible slipping, any crimping action other than that of the possible wrinkling of the beams themselves was eliminated.

In view of the above tests it is quite possible that the proportional limit of steel is lowered a certain amount, perhaps some 20 to 25 per cent, by the process of punching and riveting, and

the induced clamping strains in shapes. The matter is one for further investigations before drawing, however, definite conclusions. Some writers have considered that initial strains from riveting are in themselves quite sufficient to account for the variable sloping of the upper part of the stress-strain curves. It is believed, however, that there is another important type of strain to be considered, the second type previously mentioned, which will now be discussed as one of the probable causes of the flattening of the column curves after the proportional limit is passed.

(*c*) *Elastic and Inelastic Strains Due to Texture of Fabricated Steel.*—It has been shown in experiments by Basquin,[35] that "dimples" covering the region around rivets have been caused by the driving. The over-all thickness of two plates that had been riveted together was measured at numerous stations. The dimples were made evident by drawing on a map of the plates contour lines that showed the variation in thickness. These dimples may, in fact, often be seen in small columns of thin shapes. The force exerted by the riveting machine in driving the rivets above referred to was estimated as 40 tons. It was shown previously by Bach and Baumann [36] that this high power of clamping of riveters is not only needless, but it was stated to be actually injurious, in that the plates in the vicinity of the rivets are subject to stresses beyond the elastic limit. Various interesting cuts were given by them to illustrate the different degrees of disturbance experienced. The excess thickness in the case of Basquin's experiment varied between 0.005 and 0.010 inch as a rule.

It will be evident from the above considerations that each elementary portion of the steel between the rivets is subject to considerable initial curvature as a result of the clamping action of the riveter and the contractile force in the rivets. Each element carries its portion of the applied load on the column not alone as a straight bar, but as one which has considerable initial bending stress. This bending stress increases with the load. Since the applied stress on the element is superposed on the bending stress from curvature, the point of cold flow of the material must occur at a lower applied stress than occurs in the case of a similar ele-

[35] Jour. West. Soc. of Engrs., 18, p. 537; 1913.

[36] C. Bach and R. Baumann, "Zeit. des Vereines Deutscher Ingenisure," 56, p. 1890; 1912. See abstract, also, Jour. Am. Soc. M. E., February, 1913. They suggest lower clamping pressures in riveting.

ment which is free from rivets and initial curvature. Taking, for example, a strip of metal of dimensions 1 by ½ inch with a length between rivets of 4 inches and a mean eccentricity from curvature of 0.004 inch, the approximate formula $f = p\left(1 + \frac{ec}{r_2}\right)$ shows that the maximum stress of f in the strip is 31 500 pounds per square inch when the mean stress p is 30 000 pounds per square inch. The fact that the column as a whole develops the mean yield stress for the component shapes, even after the point of cold flow is reached may again be attributed to the ability of the material to hold its load at the yield stress, for some distance after cold flow has occurred.

There are three lengths of the elementary strip between rivets to be considered: (1) The length of l_1, before loads are applied; (2) the length of l_2 under direct compression alone; (3) the length l_3 of the chord after the strip is subject to both compression and curvature. The distortion $l_2 - l_3$ will contribute a small amount toward the reduction of the proportional limit. Calculations by the authors show that this distortion is quite insignificant in the case of the close-riveted columns until the seams begin to open appreciably at or near the maximum load on the member. This distortion in the opinion of the authors may be somewhat larger in open-work lattice columns, such as those of the Memphis Bridge.

An important point to be considered in the above connection is the fact that the average stress strain curves drawn from the compression data obtained with 8-inch gauges have in general somewhat flatter slopes than those obtained from the 80-inch gauges. The slopes are practically identical in the case of columns HC1, MY1, and U_2M_1 (Mayari). (See Figs. 30, 31, and 39.) There is a small angular difference in the case of columns HC and 31HC (see Figs. 24 and 26), and a more pronounced difference in the case of columns U_2M_1 (carbon) and LC_0LC_1 (carbon). (See Figs. 38 and 40.) A corresponding difference is also found in the case of calculations of the modulus. The mean modulus for the above columns when determined from the 80-inch readings is 29 700 000 pounds per square inch, this differing but 100 000 pounds per square inch from the mean modulus 29 600 000 pounds per square inch previously given for the entire series of columns. The mean modulus deduced from the corresponding 8-inch readings is found to be 27 600 000 pounds per square inch from the recorded compressions, and when this is divided by the constant

0.956 of the 8-inch Berry gauge, the mean corrected modulus is found to be 28 900 000 pounds per square inch, a difference in the moduli of 800 000 pounds per square inch. This difference is not large if it is considered that the open-work columns of the Memphis Bridge behave as trusses rather than rolled sections.

It is desirable that the built-up column should develop a strength in compression as close as practicable to that of a rolled section of the same dimensions. It is seen from the present tests that the working stress can be taken only about one-half that of the corresponding rolled section, if the proportional limit is considered to be the upper limit of working stress as is done by designers. The problem of determining why the proportional limits differ so widely in the two cases is one which can only be definitely determined by comparative tests of plain and riveted steels made under a variety of conditions.

4. EFFECT OF REPETITION OF LOADS

When the applied stress exceeds the proportional limit of the column there is a possibility of readjustment of stresses in the member such that a designer can not easily foresee. The effect of repeated application of load in the case of columns 34CS1, 32S1, and 31HC (see Tables 15, 14, 8) indicates that such strains as have been enumerated are, so to speak, squeezed out to a certain extent. The proportional limit is raised appreciably in column 34CS1. But equilibrium against such "lost motion" would appear to take place in time as the column receives successive repetitions of stress. The behavior of columns under repeated loads, indicated by the curves of Figs. 15, 14, and 8, is in accord with certain well-known phenomena among practical men, such, for example, that the curvature in the stress strain curve for cast iron can be considerably reduced by what is familiarly spoken of as "loading the material" before inspection. Moore [37] in deflection tests on I beams has shown that there is a gradual improvement in the elastic qualities of structural steel after various repetitions of the loading, the third cycle showing almost perfect elastic action, the effect of rest on the steel being eliminated by the smallness of the intervals taken. With the built-up steel, in view of its laminated character, a number of cycles of loading would be required to produce effects at all comparable with those mentioned for plain materials. Since rivets, lattice, pin plates, etc., ultimately take their final

[37] Univ. of Ill. Bull. 48, "Strength of I Beams in Flexure," p. 12.

positions and snuggest bearings, there is a fair amount of evidence of a probable ultimate practical conservation of the stress strain cycle in which the hysteresis phenomena described will nearly disappear. The inelastic action is perhaps most pronounced in the initial loadings from zero to 1000 pounds per square inch, for in the case when a stress strain curve is taken from zero loading a pronounced jog will often appear [38] in the curve at about 1000 pounds per square inch, after which the slope will be uniform. It will be seen from Fig. 34 that the slopes of the several curves are not appreciably changed within working loads, this indicating that the rate of stress to strain is not materially affected.

5. GENERAL ACTION OF LATTICE

Several kinds of lattice bracing have been presented for comparative examination in the various columns under consideration. The lattice used may be subdivided into two general classes. One consists of either a double or single set of diagonal bars in series superposed on the several column ribs which are either two or three in number in the columns of the investigation. The other employs, in addition to the double diagonals, transverse bars placed between successive panels of diagonals. The columns of the Municipal and Memphis Bridges have the first type, while the second is peculiar to the members for the Metropolis Bridge.

In determining the laws of action of these general types of lattice, it will first be broadly stated that the ribs of a column, considered apart from the lattice bracing, are very flexible pieces, as may be seen when they are lifted by a crane during fabrication. This point will be used in the interpretation of results. The ribs are moreover the main carriers of the load, offering the most direct paths for the stress and having the greatest rigidities (defined as the reciprocal of the strain). Very little strain energy of the column is absorbed by the lattice in columns of the small slenderness ratios under consideration here, this being greatest at the ends of columns close to the large batten plates on account of the large restraints imposed at these points.

A differentiation must be made as to the manner of connection of the bars to the ribs. The lattice of either type is mechanically intermediate to two abstract cases which are presented in analysis: One is that case (*a*) where the joint connection may be considered frictionless without any restraint to rotation of bars about the

[38] See Buchanan's curves, Engineering News, p. 685, Dec. 26, 1907.

joints. This is best realized practically by a single loose rivet or bolt connection of bars to ribs. The other is the case where (*b*) the angles between the ends of lattice and the ribs are completely conserved during strain, by rigid connections of the bars to the ribs, such as is approximated practically by a two or three rivet connection. The bars in the latter case when the column is loaded will be bent by variable stress couples acting throughout their length, which are brought into play, in addition to some direct strains in the bars, by reason of the fact that the triangular and quadrilateral elements or cells of the linkage formed by the lattice network are warped slightly from their initial shapes by the straining. The lattice bars can only accommodate themselves to the new configurations by being bent into flat curves, which in general have a point of inflection. In any actual lattice system which is intermediate to the limiting cases (*a*) and (*b*) the direct strains in the bars are found first upon the assumption (*a*) because a slight change in the configuration of the network formed by the bars and ribs does not appreciably affect the values of the direct strains in these members. The flexural stresses are then analyzed by the method of secondary stresses upon the assumption (*b*) of rigid connections at the apices. The resultant action is gotten by the superposition of the two strain systems, according to the usual practice in structual design.

(*a*) *Behavior of Ordinary Lattice Analyzed.*—Considering columns U_2U_3 and U_8U_9 the mechanical action under type (*a*) is that which will occur in a pantograph linkage formed by the bars, when it is superposed upon the three-column ribs. As the ribs contract under load from the testing machine the pantograph of bars merely draws together in the direction of the column axis so as to cause a slight bowing out of the outer ribs, the inner rib remaining quite neutral as to flexure and taking only direct stress. The theoretical effect upon the individual bars in the body of the columns and apart from the regions of the end battens, is to cause them to largely experience, neglecting minor considerations, that motion of translation and rotation which is defined mechanically for the rigid body, viz, one theoretically without strain. The configuration of the bars before and after strain is shown in the case of column U_8U_9 in Fig. 69 (*a*). The effect of the several transverse diaphragms causes constrictions to this action to some extent, as is indicated. The almost purely kinematic action that is occurring may be most easily illustrated in bracing

of this type by contructing a simple model to depict the behavior. Three rubber bands may be placed under equal initial tensions to simulate the unstressed ribs, and lattice of deal sticks may then

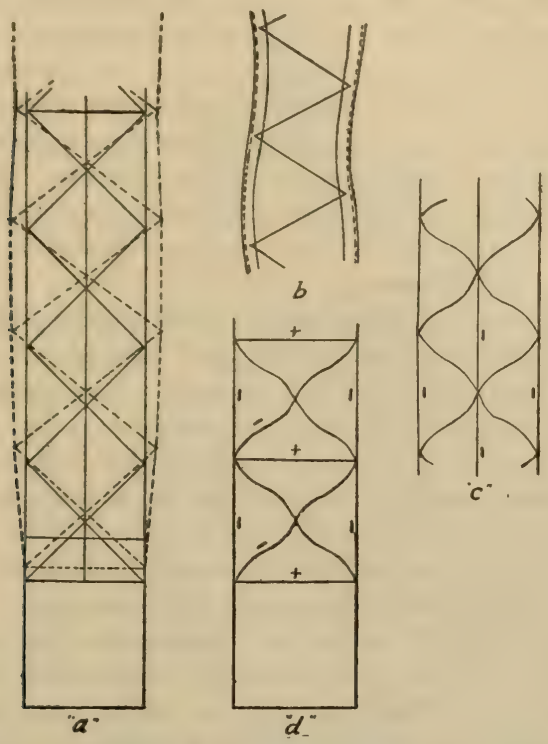


FIG. 69.—*Behavior of lattice*

be fastened upon them by thumb tacks or other means in the manner of the braces of $U_2U_3U_8U_9$. A somewhat elastic cross-piece may be placed at certain intervals for the diaphram and wider stiff pieces at the ends for the battens.[39] As the system is allowed

[39] While the action here depicted appears to be well known to practical engineers engaged in the work of column fabrication, and has been already variously termed "the accordeon effect," "hat rack action," etc., it seems to be ignored by column authorities who seek to explain the elastic behavior of column lattice by methods which assume a flexural action in the column units as a whole. The above considerations however, are believed to indicate the essential and controlling factors for the "stocky" type of columns here considered, and, in fact, should be taken into account to a large extent in columns of slenderness ratio up to 120 l/r. In the opinion of the writers this behavior is shown very clearly and in an exaggerated manner in column T_5B (long) tested by the Phoenix machine for the Quebec Bridge Commission (Engineering Record, Nov. 19, 1910, p. 568). The "bowing out" of the "ribs" as the lattice X's draw together occurs just as is found in the small model, and as is illustrated for U_8U_9 in Fig. 69 (*a*). There is a very complete constriction against this "bowing" of the ribs at the transverse diaphragm, which is clearly depicted in the sketch of column T_5B. While there is undoubtedly a small flexural action present in general, in addition to the above action, its influence is thought to be insignificant in well-designed columns under 60 l/r. Inasmuch as no theoretical flexure occurs under the critical length as determined by Euler, such actual flexure as is present must be attributed to the tendency of the bars to form unsymmetrical configurations with respect to column axes, on account of actual inequalities existing in the elastic properties of the ribs and lattice bars varying degrees of snugness in rivet connection to bars of ribs, etc., and some eccentricity of loading.

to contract to simulate the direct strain of the load from the testing machine, the translation and rotations of the bars will be seen to occur as described; there will be the constrictions at the "diaphrams" and the discontinuities at the ends due to the constraints of the battens.[40] A more perfect model for the magnification of any type of strain desired, and for any network, may be gotten by the use of telescopic types of flat strips, where any configuration, apart from the original unstrained status is obtained by taking arbitrary displacements in the elements, either plus or minus, to suit the class of strain, and reclamping for the final configuration. This can be done for the bars as well as the ribs, to best suit the conditions.[41]

A fair experimental verification of the above actions in the columns U_2U_3 and U_8U_9 will be obtained through an examination of $\pm$ elongations given for these columns. (See Tables 3 and 4.) The strains for the lattice of U_8U_9 under station 33 and 34 are found by dividing the ($\pm$) elongations by eight, the gauge length. For the entire range of loading to failure they never reach 0.0001. The stresses found by multiplying the strains by the modulus = 30 000 000 pounds per square inch vary throughout the range of loading between 0 and 1200 pounds per square inch. Taking the bars of U_2U_3 and U_8U_9 nearest the diaphragms they range somewhat higher from 0 to 2500 pounds per square inch near failure, and generally for working loads in the bridge never greater than 1200–1500 pounds per square inch, as is expected. On the other hand, the effects in bars of panel next the battens are much more pronounced, being for working loads from 0 to 9–12 000 pounds per square inch for U_2U_3 and with a tendency to overstraining at higher loads. In view of the fact that the stresses practically are not always negative—i. e., compressions—the strain system evidently is not perfectly symmetrical about the axis, as in the theoretical case. This is due to more or less actual assymmetry with respect to elastic properties of the bars, readjustments and play of holes in lattice, and perhaps some slight flexural action in the columns which can not be strictly taken into account practically. With longer portions of ribs between the cross diaphragms, or with these diaphragms omitted, the pantograph action would more perfectly

[40] In the Steubenville Bridge tests (Pennsylvania Lines) it was conclusively shown that where single-riveted lattice is used there is no strain in the bars at a distance from diaphragms, etc. In the present investigation attention was given to the strains in bars close to the transverse diaphragms and end battens where certain strains are maxima. (See Fig. 2, Pl. XXXVIII, Trans. Am. Soc. C. E., Vol. LXXIII, 1911, p. 443.)

[41] Mich. Technic, February, 1909, p. 34.

approach that described and the stresses of the bars be correspon-d ingly less in the body of the columns. Reference may be made to the tests by Howard on the Steubenville Bridge columns in this connection for a closer verification. Talbot and Moore state in their paper "the amount of deformation observed in lattice bars is relatively small."

It may be remarked that in certain inward bucklings of bars, the phenomena are those of failure and not elastic action. They only appeared toward the end of the tests and were first discernible as shadow effects on the lattice, denoting the immanence of failure. (See photos after failure.)

(*b*) *Action of Lattice in Deforming the Column Cross Section.*—It will be seen also in studying the action of the lattice bars in members of the type of $U_2U_3U_8U_9$ either with three or two ribs, that as the separate X's of the individual panels of lattice flatten out they exert collectively well distributed pressure outward on the rib flanges, causing bending in the webs of ribs about the longitudinal diaphragm as a fulcrum. This is not only evidenced by the more frequent tendency to compression stresses in the lattice but by the extensions on the cross diaphragms as given by the elongations under stations 41–42 of U_8U_9 and 17–18 of U_2U_3. (Tables 3 and 4.)[42] It is difficult to attribute these elongations to other causes. They are rather large, considering the otherwise relative rigidity of the columns. Taking the restraint of the continuous longitudinal diaphragm into account with the outward pressure of the lattice taken as a whole, the cross section of the members of this type then tend to be bent into the form shown in Fig. 70. This bending will be least at the cross diaphragms, of course, and greatest between them where the flattening out of the X's is least restrained.

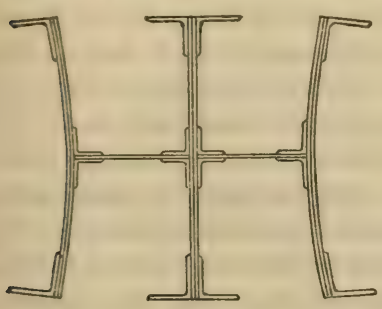


FIG. 70

In view of the tendency of large strains in the battens due to the "spreading" effect of the lattice, the angle at the edge of the battens seems a wise provision of the designer in preventing overstraining. This point will be taken up later in other columns.

[42] Column U_2U_3, on account of the closer spacing of diaphragms, is subject to more local perturbations than U_8U_9, which have a modifying effect on the action of lattice bars, which has been described. But in general the law of action is as described.

The ribs just at the batten experience rather severe bending in most of these types of lattice.

(*c*) *Flexural Stresses in Ordinary Lattice.*—In the analysis of the purely kinematic action in the columns of nickel steel, U_2U_3 and U_8U_9, the configuration of the strained system of lattice and ribs is found by connecting the displaced positions of the joints by straight lines. The flexural actions now to be described exert no appreciable influence in modifying this configuration for direct strains, except that the neutral axes of the bent bars will in general deviate from the straight lines connecting joints, the deviations being zero at the ends of lattice bars and at the point of inflection of the neutral axis. This is owing to the fact that in the case where there is a flexural system due to the moments of restraints caused by the riveted joint connections at the apices the changes in the lengths of the ribs and lattice are still those of the direct strains in the pieces. The length increments ($\pm$) due to the slight curvatures experienced in the flexure of the bars or ribs per se are negligible, since for the flat curves considered in elastic analyses the arc does not sensibly differ from the chord. In other words, the decrement due to the curving is relatively small compared with the compression or extension from direct stress. The flexural stresses will be most apparent where there are wide bars well riveted at the ends or intersections. In general, if extensometer readings are taken at the outer edges of the latter, the differences between the measurements show that flexure is taking place. By reference to the elongation data on the wide bars of column MY (Mayari) (see Table 7) and column US_2MS_1 (carbon) (see Table 16), it will be seen that these flexural effects are often pronounced even for the common range of working loads. On account of the relative width of the bars, however, no refinement of analysis is possible, as the beam principle, of which Manderla's method is a generalization, is only applicable strictly to more slender lattice. The average of the strains determined give the direct strains on the axis. The difference between this axial strain and that at the outer fibers of lattice bar is the mean bending strain in the piece. In view of these remarks it will be seen that as the column ribs contract under load, these wide bars must take considerable flexure as shown by the data to accommodate themselves to the new configuration imposed by straining. As the rivets are sufficiently far apart at the joints to cause strong moments of resistance at the ends of lattice, a series of these moments act on the column

ribs throughout their length. The question here raised is, of course, largely one of efficiencies in proportioning the material and not particularly one of the strength of the column as a whole.

The general type of flexural strain occurring in U_2U_3 and U_8U_9 is shown in Fig. 69 at (*c*). Taking into account the method of secondary stresses, this follows directly from the following considerations, but it was also confirmed by trial with a model of the kind already described. The direct strains in the ribs cause the angles at the joints formed by the axes of the bars which face longitudinally to the column to take small angular strain decrements, whereas the angle between the bars at the joints is maintained constant by the rigidity of the connection. The bars then are bent into the flat reversed curves indicated. By reason of the essential symmetries of the strain system in the mid panel between diaphragms, the point of inflection occurs approximately at the mid point of the bars. The constriction of the transverse diaphragm simply modifies this flexure in degree, and causes a displacement of the inflection point along the axis, the action evidently being most severe at the end battens where considerable flexural stresses must occur. There is every indication that the bending in the rib near the batten is very abrupt.

The outer ribs of these columns are in general flexed in the wavy type of curve usually shown for the continuous beam. This follows from the fact that the end stress couples of the pairs of bars proceeding from the joints along the ribs can not be equal, except in the ideal case of a column having long ribs without constraining diaphragms where a perfect symmetry of the different strain configurations about the column axis may be assumed to exist. Readjustments in the lattice and differences in the elastic properties of the material will also have an influence in causing the ribs to be bent into sinuous curves.

(*d*) *Action of Lattice in Modifying the Continuity of Strain Distribution.*—The essential point to be considered and brought out in a study of the latticing of the columns of this investigation is not the extent of the strain so much, as this is small, as its character and influence with respect to the strain deportment of the column as a whole. With perhaps one or two exceptions, to be discussed, there would seem to be no special action in the lattice here present, either with respect to its strength or the particular type used, to influence very appreciably the strength of the column considered as units. It is thought, however, that it can be shown there are

actions introduced by certain types of lattice which will make it quite doubtful that the principle of mechanical continuity which the designer assumes and desires shall always hold throughout the range of loading. It is this point, it is believed, that should chiefly be considered in a study of the deportment of lattice systems. Those who have aimed to formulate a mechanics of the columns have of necessity based it upon elastic principles, which imply that the system of strain shall be continuous and derivatives of the first and second orders shall exist during the range of working loads. In other words, in designing the stress couple along the column $\left(\frac{d^2y}{dx^2}\ EI\right)$ is taken proportional to the curvature of the strained centroidal axis as in a beam $\left[M \propto \left(\frac{I}{r} = \text{curvature}\right)\right]$. A superficial examination of the results of many investigations is sufficient to show that the crux of the situation is largely to be found in the effects of the lattice. In the present investigation the variability of the action could often be noticed in the rate of taking load, the sounds and creakings accompanying readjustments, etc. It is not that difficulties of this description can be overcome entirely, but perhaps in the light of investigations they may be more perfectly understood and the conditions ameliorated by taking due account of them in design, as will be shown later.

(*e*) *Assymetrical Action of Single Lattice.*—In single latticing there is obviously assymetry of configuration of the bars and the strain system about the axis of columns. The elastic lines of the outer ribs are unsymmetrical in general, as shown in Fig. 69 at (*b*). This is equivalent to an essential eccentricity of the loading. In the struts of column US_2MS_1 (carbon), the designer has counteracted this assymetry by an ingenious arrangement of balancing one component strut of the column against the other. The unsymmetrical action of single lattice was further shown apart from theoretical considerations by a model. The main distortion occurred at the ends of ribs next to battens. Although this "balancing" of the lattice was arranged in columns LC_0LC_1 of both steels, it is suggested that the unsymmetrical character of the lattice has very probably contributed to the failure as presented, in spite of the effective breadth of the member in the plane of distortion and the care exercised in the design.

(*f*) *General Character of Failures in Columns with Ordinary Lattice.*—It will be noticed that all of the columns using the ordi-

nary type of lattice (omitting those which bent at the pin plates) failed with what may be called angular fractures. These were of the type somewhat comparable to those presented in a short prism and ordinarily spoken of as shearing failures. Or they failed locally apparently from the effects of the lattice, in acting unsymmetrically with respect to the column axis. The theoretical considerations based on Manderla's method show that the stress couples at the joints will be maxima or minima (or more properly "extrema"). In view of the reduction of area in the ribs throughout rivet holes, the action of internal strains, and the possible occurrence of fortuitous combinations of untoward stress couples, the rib at point of connection with lattice is usually the weak point in most columns of small slenderness ratios. The failure in U_8U_9 at the joint (see Fig. 42) may be noted. That this is not as well borne out in this investigation as in some others is attributable to the uniform excellence of the designs and fabrication of the members throughout.

(*g*) *Behavior of Lattice with Transverse Bars.*—In the ordinary lattice already discussed it was seen that in considering the system of lattice as a linkage superposed upon the ribs, relatively speaking, considerable freedom of motion is permitted as the ribs contracted under stress. In the case of the Metropolis Bridge columns the linkage action is almost completely restrained by the transverse bars. Whatever motion occurs must either be due to the elastic action of the members themselves or to some inelastic play at the rivet connections as the load progresses.

The main function of the transverse bars, the tests show, is to largely prevent the tendency of the outward bowing of the ribs as the column compresses and the X panels tend to draw together. The elongations for the transverse bars as given for columns MY, MY1, 32S, and 34CS1 (see Tables 7, 9, 12, and 15), taken in general, show strains averaging from 0.00005 to 0.00010 for column working loads of 10 000 to 20 000 pounds per square inch. With a modulus of 30 000 000 this implies stresses of some 1500 to 3000 pounds per square inch. In examining the action of the lattice bars, it should be noticed that where the measurements include spaces having riveted connections to the ribs that the strains are indeterminate analytically, but nevertheless show experimentally the real action that is taking place. Some of the results must accordingly appear somewhat erratic on account of the perturbations indicated in the bars by the rib portions in contact with them.

In a study of the stresses of the diagonal bars it is logical upon first examination to expect these also to resist outward bowing and be in tension, as are the transverse bars. The controlling influence, however, is again the main axial compression in the ribs, and accordingly (from Kirchhoff's law for subdivided currents which also applies to stress) these bars are in compression, taking their portion of the axial load from the testing machine with the ribs, since they can not move in the manner of the previous type of diagonal bars. An examination of the data of column 32S shows that the strains are of the same relative magnitude as in the transverse pieces. The components of the diagonal strains do not balance necessarily those of the transverse bars, for a portion of the stress is taken by the diaphragms and end battens. The system is statically indeterminate.

There is evidence of large local strains at the batten edges, and perhaps the same reinforcing angle here as was used in the case of U_2U_3 and U_8U_9 of the other type would be efficient. The transverse diaphragms are not as essential in the present case as in the other columns, as the transverse bars undoubtedly prevent any considerable outward bending of the rib flanges about the continuous longitudinal diaphragm as a fulcrum. The chief function of the transverse diaphragm is to reduce twisting and warping of the shaft. The abrupt bending of ribs at the battens is largely eliminated by the transverse braces.

It has been suggested to the writers that the lattice of these columns of the Metropolis Bridge designs should be larger—more comparable in size to the transverse bars. It is the opinion, however, that in view of the fact that the loads of long span bridge members are intended to be axial, scarcely any more metal is needed in these diagonals than to take up such transverse loads as occur from gravity, and some actual column flexure which may occur as a result of the initial eccentricity. This could be determined on the basis of an arbitrary shear taken as a small per cent of the axial load.[43] It is considered more logical to have the lattice flexible enough to bend and adjust themselves after the range of working loads has been well passed. Otherwise the diagonals will store up considerable strain energy which more properly should be absorbed by the ribs, the main carriers of the stress from loadings. In view of the preponderance of the strength of the columns of this series having the rib flanges turned out,

[43] This has already been suggested by a number of engineers.

with lighter lattice, over those where they are turned in and heavier lattice are used, there is nothing to indicate that the more slender diagonal is inefficient in any manner whatsoever. It was apparently the intent of the designer to obtain data covering this point.

In this type of lattice the bending stress is of the same character as before, the transverse bars in the main remaining neutral as to flexure, except as slight assymetries in the strain configurations exist and moments at joints occur to modify this. (See (*d*), Fig. 69.) With the wider bars, however, as has already been shown the flexure will be rather large, which is believed to be another point in favor of the more slender diagonals.

(*h*) *Comparison of the Two Types of Lattice.*—As far as the relative efficiencies of the two types of lattice are concerned, it is perhaps too early to pass upon the comparative merits of the systems presented, as this will fall more properly to the province of designing engineers. Moreover, a larger number of tests would appear desirable before very complete judgments can be formed as to the mechanical principles which control. The fact has already been mentioned, however, earlier in this paper that the 10 columns of this series failed in smooth curves with inflections corresponding to those commonly given in the mechanics of materials for a pin and square or two square ends according as the deflection was perpendicular to or in the plane of the pin. If this uniformity of action is properly traceable to the influence of the transverse bar type of lattice, and it is believed it is, it would be an excellent feature to introduce these additional bars between panels into column design with a view to conserving the cross sectional form of the column and insuring a more uniform action of the lattice throughout the entire range of loading than it has been possible heretofore to obtain, judging from previous tests. If the deportment of the column as a unit can be controlled in a manner which is in closer conformity with those theoretical postulates which have been laid down by experts in the past, but which have been so often found to be violated as shown by the practical behavior during tests, it is desirable that any mechanical features in construction which will contribute to this end are worthy of further study and experimental investigation. The writers will recommend that the transverse bar be studied and experimented upon further on the basis of the good results obtained in the present tests.

6. BEHAVIOR OF PIN PLATES

(*a*) *Slipping of Pin Plates Discussed.*—A study of the compressions corresponding to stations 15 to 16, 17 to 18, etc., on columns 31HC, 31HC1, 34CS1, 32S, 32S1, Figs. 26, 32, 34, 27, and 33, will show that there is in general a difference in the values for the parallel gauge lengths, these being taken so as to show any relative displacement of one plate upon the other, for example, as at stations 15 to 16 of column 32S1, and similarly for the others. In the stress-strain curves corresponding to these stations the curves whose abscissas are the average compressions for 15+19 and 16+20, etc., are platted side by side. The resultant curve adjoining, which was gotten by algebraic addition of the separate abcissas, shows the detrusion of the plates. The shape of the latter curves indicates the relative movement is increasing quite uniformly with the loadings from the beginning of tests. This slip in some cases could be actually discerned by the "stepping" of the originally plane surface at end of pin bearing.

The movements above described are partially elastic. An examination of the pin-plate stations of columns 34CS1, which was especially studied under repetitions of loading, show that when a load of 10 000 pounds per square inch was applied, and a repetition was again made at zero, that there was a set averaging from about one-half to two-thirds of the relative movement of the plates. It is difficult to assign the cause of this absolutely. Doubtless it is made up of a combination of effects from some infinitesimal play in holes, initial strain in and around rivets, etc

After several repetitions of the load it will be noted in many. cases that there is finally realized a tendency to reduction of the areas of the stress-strain cycle as if the sets, so to speak, were "ironed out," by the loading as in the previous discussions. For example, under station 15 of column 34CS1 (chrome) at the three successive loadings of 10 000 pounds per square inch, the compressions in 16 inches are 0.0042, 0.0042, and 0.0043 inch, the values at 1000 being 0.0011–0.0010 inch, as if a final equilibrium were taking place. This is fulfilled in some of the others. In several cases a marked discontinuity occurs, as, for example, under station 21 the three compressions at 10 000 are 0.0076, 0.0091, and 0.0124 inch, respectively, a progressive action, the compressions at 1000 being 0, 0.0021, and 0.0051 inch.

In the mechanics of deformable media overstraining at a point or small region generally merely causes a local change in the density

of the material in the region under consideration, so long as the general strain configuration is not changed and fissures or cracks do not develop. If the continuous web of a column at the pin is overstrained so as to cause a slight flow of the material at the pin, probably the most direct influence would be exerted in decreasing to some slight extent the configuration of the truss, without affecting the column strength, except as the truss was deformed itself and a redistribution of stresses occurs in the members. The column U_2U_3 in which the movement of the plates was most prominent is, in fact, noteworthy also in failing at the highest load with reference to the yield point of its steel. (See Fig. 43.) The effect of a movement of plates on the truss pin, however, would be relatively more important and probably would cause a readjustment of forces and a change in bending moment of the pin. It is believed therefore in this respect the tests, taken into account with other investigations, show that a further study of the causes which affect detrusion of plates is advisable. The length of plate is manifestly not the only variable to be considered, and the initial strains on rivets undoubtedly play a part.

An examination of the views of columns taken after failure indicate that the designers in all cases have effected a gradual absorption of the strain from the pins into the bodies of the columns. There is no evidence of that buckle in the web at the end of pin plates (with the exception of US_2MS_1) which is so prominent in many previous tests, and which is caused by too abrupt a transition in the flow of the strain and stress into the webs. The fact that such a large percentage of the members failed as units, in comparison with previous investigations, offers abundant evidence that efficient designing of details can be easily assured in engineering practice.

In the case of the four columns failing at the ends, the problem of designer was a rather difficult one, owing to the long jaws required for egress of eye bars. In spite of the large battens and transverse diaphragms used a local failure occurred as is shown in cuts. An idea of the transverse component causing buckling in US_2MS_1 (Mayari) is gained from the fact that 14 rivets are simultaneously sheared (see Fig. 57) at the local failure.

(*b*) *Distribution of Stress and Strain near Pin.*—In measuring strains or displacements around the pin 8-inch gauges were used to give sufficient magnification to the deformations, which are not in any event large. Two-inch gauges would have been

better for defining the field of stress, but on account of the thickness of the plates, the proper clearing of rivets, etc., the 8-inch gauges were used and will give a better practical and experimental determination, from the engineer's standpoint, of the behavior that occurs in this vicinity. On account of the more rapid rate of variation in the stress and strain close to the pin the mean functions taken in 8 inches will, of course, not afford much idea as to the exact values of the stress constituents at this point. Some approximate idea of these may be gained by an examination of related problems which may be referred to in this connection.[44] The problem of distribution is complex viewed theoretically, but keeping certain essential points in mind, it will not be very difficult to analyze the distribution with respect to the practical engineering points at issue and also theoretically, for the controlling factors.

The stress field in the neighborhood of pin may be very appropriately called a fan distribution from certain analogies presented in the surface loading of beams as given by Sir G. G. Stokes.[45] While designers recognize the general character of stresses to be met here, few, if any, critical studies have been made in defining the intensities, and the common assumptions in some cases are not actually realized experimentally. The matter has been left largely to the judgment of the designer.

Taking up first the distribution of stress upon the pin at the base of the fan (see Fig. 71), specifications call for the stress on the bearing plates and webs of columns per unit of thickness, to be determined by dividing the working load on the plates by the diameter of pin. This is tantamount, of course, to the assumption of a uniform normal pressure over the periphery of pin. Obviously, such a law can not even approximately hold. A normal pressure on the pin surface varying as the ordinates of a parabola from zero to a maximum just over the pin would be more in accord with mechanical methods, for a first approximation to the stress constituents on the surface boundary at pin. In the case of column U_2M_1 (Mayari) a study of the compressions at stations 35, 36, 37, and 38, Table 19, show that the maximum intensity of

[44] See Chapters VIII and IX, Love's Theory of Elasticity, 2d ed. Also Comptes Rendus, Tome 114, 1892, p. 1467, "Sur la répartition des pressions dans un solide rectangulaire chargé transversalement," by Flamant.

[45] Discussed by Sir G. G. Stokes in paper by Wilson, Proceedings Physical Society of London, Vol. XI, 1891, p. 194, The Influence of Surface Loading on the Flexure of Beams. Also by Love, Theory of Elasticity, 2d ed., p. 351.

stress is on the axis just over the pin [46] and that there is a rather pronounced decrease at 35 to 38 from 36 to 37 and more so as one goes from the axis laterally. In the case of column HC (car-

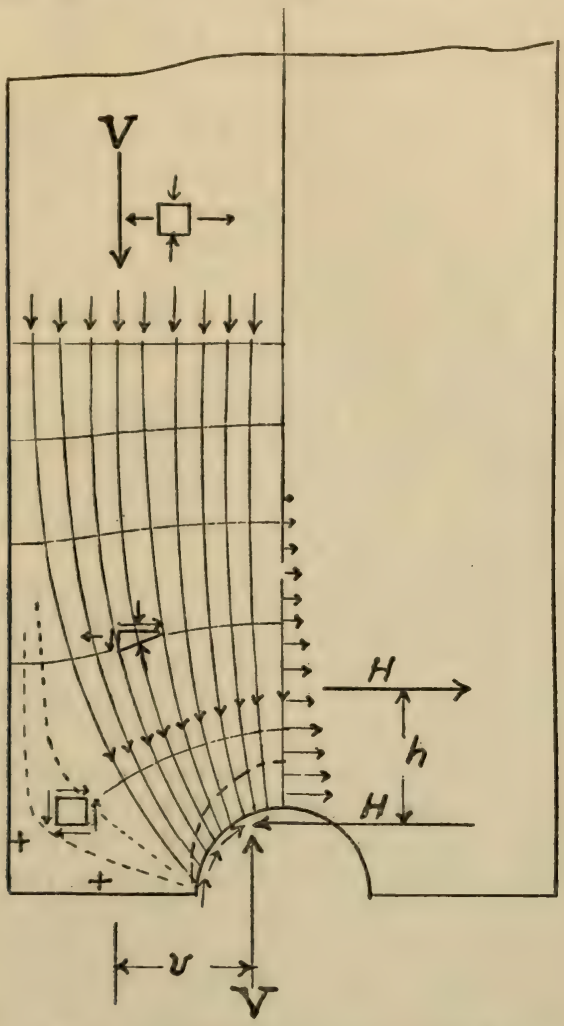


FIG. 71.—*Field of strain at pin (conceptual)*

bon), see Table 6, the distribution over the pin is more uniform, but the influence of the longitudinal diaphragm is thought to be present here to modify the action described. Now as rivets are designed for bearing and shear with respect to their uniform dis-

[46] This is a common physical phenomenon; for example, when a positive electrode is placed conveniently near an equally strong negative electrode, these constituting a "source" and "sink," the main flow is in the straight line between them, but a portion will spread out over the intervening medium in the above manner. In the present case, carrying out the analogy, the column may be considered "grounded" at the upper end, the strain energy being transmitted from the pin through the member.

tribution on plates, it will be rather obvious, in common practice, that there is a tendency for rivets to be overstressed just over the pin. This, it is believed, is a contributing influence in causing the slip in plates. The play usually allowed in pinholes augments the tendency to concentration of the load on plates at the pins to the portion in region of column axis.

Analytically, there should be considered a friction stress on surface of pin, due to the wedging down of column on pin, this being in the main symmetrically distributed as in the preceding case and, upon the usual assumption of a constant coefficient of friction, varying as in the case of the law for normal stress. When the flexural moment in column causes an appreciable turning about the pin, which is not believed to occur until an advanced stage of the loading is reached, the law of course will change and the friction will resist the flexural action of column. The frictional stresses are then no longer symmetrically distributed, or approximately so. The imperfect symmetry of distribution sometimes existing at the earlier loadings is believed to be due to slips and readjustment in the parts as a result of column flexure, as has been mentioned for other cases.

In related problems of this kind there is a practical boundary to the compression area as defined by the lines of principal stress composing the fan. The differential equations for these lines are ordinarily independent of the load and may be found as soon as the stress constituents are known.[47] There is a neutral area beyond the region of compression at the lower corners of columns in which the strain is mainly rotational, distorting the material without a volumetric compression of the steel. The evidence of this region is shown in the tests by the smallness of the measured direct strains and the fact that they change from compressile to tensile. Reference may be made to the character of the elongations at stations 42, 43, 44, and 45, etc., of column HC (carbon), Table 6. If compressions occur at the outer stations, they are low, being reduced by the general tensile tendency of the stress on the outer face of corners. In these neutral regions at the lower corners the rivets are ineffective and offer little help until a movement of plate is caused by the heavy compression over pin when a redistribution of stress occurs, and the rivets at these "dead ends"

[47] The question of the existence of stress functions which shall be congruous with any assumed law of stress distribution at the pin or over the cross sections of the body of the column is not one that need enter here. Even in analysis these can usually be expressed only as "average stresses" in this type of problems. Suffice it to say, however, in any practical case the laws of variation can be found by suitable convergent processes, i. e., successive approximations, which will serve all the needs of the designer.

then help in distributing the stress. In the analysis of stresses in pin plates of the Steubenville Bridge test columns it was stated that the lines of boundary of the compression area over pin should be taken at 45°. An elliptical boundary is, however, more in accord with theory and other experimental determinations. The rotational character of the strain in the "dead end" portions is accounted for by the region being caught up between the confluence of strains of opposite sign which bound the triangular-shaped vortex of the region.

(*c*) *Splitting Action of Pin on Web and Plates.*—Although few observations are recorded here to show the type of stress to be described, it is important also to mention that there is a wedge or splitting action of pin on the column web plates that is never considered in specifications, and it will be well to investigate it in connection with this stress distribution. Taking into account the static equilibrium of the half-section at the pin shown in Fig. 71, the line of upward pressure on the pin surface does not coincide with that of the resultant of the fairly uniform direct stress on the half cross section of the columns. There is then a stress couple Vv, which must be resisted by a couple Hh, composed of the horizontal stress area over the pin acting with an effective arm whose length is equal to the distance along column axis between the line of action of the outward thrust of the pin and that of the resultant of the stress area covering the region of splitting action [48] above the pin. As the only other horizontal stress to consider in the equilibrium of the half section is the outward component of thrust of the pin, the stress area in question must be equal to this thrust. This would be determined as the sum of the effective components of normal and frictional stresses on pin already mentioned and would be difficult to determine by direct experiments. As a first approximation this stress may be assumed to vary as a linear function of the distance from pin along axis, this being the simplest function which vanishes at that point where the direct stress is finally uniformly distributed over column cross section, for after this point is reached the major principal stresses being coaxial with column and the column surface free of stress, no horizontal stress on the axis is needed to maintain equilibrium.

The general character of all the limiting stresses, so far as they are needed in this discussion, have been indicated in Fig. 71. In

[48] Columns have been noted to split at the pin plates in tests. (See, for example, Fig. 6B, p. 687, of Buchanan's tests, Eng. News, Dec. 26, 1907.)

column U_2M_1 (Mayari), Table 19, the readings at stations 46 and 48 will show the amount of this horizontal "splitting" stress for working loads is not large, the value for 46 close to pin undoubtedly being influenced by the frictional components perpendicular and transverse to the pin at its surface. Taking, for example, as an approximate determination, the elongation at a load of 26 960 pounds per square inch is 0.0026 inch under station 48. Subtracting from this the natural expansion under the compression load or (Poisson's ratio = 3/10), 3/10 of the mean compression as found from averaging corresponding readings for stations 27, 28, 29, 30, 35, 36, 37, and 38 (= 3/10 by 0.0051), there is found 0.0026 − 0.0015 = 0.0011. Which corresponds to a tension of 4200 pounds per square inch on basis of $E = 30\,000\,000$, as an average value for the intensity of the stress resisting splitting action at a point on the column axis and near the pin.

The distance from the pin at which the stress becomes fairly uniform over the cross section, as is evidenced by the compressions converging to a common value, is seen to be approximately at the end of the second pin plate in column HC (carbon), Table 6, and near the end of first plate in U_2M_1 (Mayari), Table 19. They are, in other words, long enough in this respect.

That there is evidence of internal strain, probably of the character already discussed in connection with those due to rivets, to be considered in connection with a study of the strains and stresses in pin plates, also possibly some small flexural action in the column, is evidenced by the unsymmetrical arrangement to some extent of the distribution, as may be noticed in the elongation reading under stations symmetrically taken with respect to the axis. This is believed to be due to imperfect unisons of action of the parts rather than any bending proper in column. Of course there is some bending moment at the ends of the column, but what its real action is and its amount is more or less indeterminate. From the fact already mentioned that the deflections only are apparent near failure, the writers are led again to believe that the short column action is maintained within limits through the greater portion of the load.

V. SUMMARY AND CONCLUSIONS

1. REMARKS

The 18 test members were of modern design and workmanship and were straight without defects from handling. It is believed the columns are representative of the most recent engi-

neering bridge practice in the construction of members for long-span bridges and that the tests will throw considerable light upon the behavior during tests that may be expected of other columns of the same general type of construction. The members were preliminary studies of the designers. The purpose of the tests was to determine the strengths of the columns under intended axial loads and to obtain data for studying the laws of distribution of stresses in the columns with a view to estimating the probable strength of the full size chord members in the bridges.

2. RECAPITULATION

1. Twelve of these 18 columns failed as units, viz, the two test members of 3¼ per cent nickel steel for the Municipal Bridge and the 10 specimens of Mayari, chrome, silicon, and high-carbon steels for the Metropolis Bridge. When the maximum loads as determined were platted as functions of the grades of steel used in their fabrication, the mean curve taken through the centroids of the groups of observations showed a fairly close agreement with the mean curve determined by averaging and platting the respective mean yield points as found for the corresponding test pieces. The average deviation of the maximum loads for the 12 columns from the mean yield point of all the test pieces was ½ per cent. The minimum and maximum deviations in absolute values were 3.7 and 12.5 per cent. The curve for the failures fell within the zone bounded by the curves of high and low yield points with two exceptions, one point being just above and another just below this zone.

2. Four test columns of the Memphis Bridge failed locally at the ends, which the experiments showed was largely incident to difficulties experienced by the designers in providing for sufficient space for the eyebars at the pin connection. The two remaining test members failed in the plane of greatest theoretical strength, apparently due to the lack of full unity of action of the component ribs of which the columns were composed, the effective strengths of the ribs, as determined experimentally, being less than that expected for the columns as a whole, although one of these members of Mayari steel was well within the zone of failures as defined by the extreme yield points.

3. Taking into account the failure of the nickel and Mayari steel columns at stresses of 3000 to 5000 pounds per square inch above the mean yield point, and the chrome and silicon steel

members about the same amounts below it is believed that there is some indetermination to be expected in obtaining the real strengths of these members in contradistinction to the effective strengths as recorded. In view of the care exercised in centering the columns and insuring parallelism of the bearing plates to the platens of the testing machine, it is considered that a certain small portion of this indetermination is largely inherent in present testing-machine practice, because of the impracticability of determining precisely the true center of pressure of the resultant force for pin and square bearings. The remaining and larger portion is believed to be incident to the fact that there is not a perfect unity of action of the component steel shapes in distributing the stress from load, this, however, being most in evidence after the region of yield points are reached and redistributions of stresses are occurring.

4. The specimens are too few, considering the variations in the grades of steel used and differences of design, to make precise inductions (apart from the larger field of experimentation already conducted on large columns) which are favorable to existing types of column formulas. As the columns have a range of slenderness ratio of 15 to 43, the influence of a column reduction factor would be less than some of the deviations from the yield point as found experimentally. The behavior with respect to the deflections and variation of stress in the members, however, leads to the opinion that a reduction factor is unnecessary for calculating strengths within the range of slenderness ratios existing for the columns.

5. In the 10 members for the Metropolis Bridge, the lengths were constant and the cross sectional areas equal (very nearly) throughout. The strengths of those columns having the flange angles turned outward and thinner webs and lattice, when referred to the mean yield points of the respective steels as datum, was greater in the ratio of 3:1 than in the case of the more compactly built members having thicker webs and wider lattice, the flange angles being turned inward. As many engineers are of the opinion that stocky columns $\left(\frac{l}{r} \text{ small}\right)$ can be designed without special reference to a cross sectional form factor, such as the radius of gyration, the tests appear to show that there is for such columns as for more slender members an effective distance from the column axis for placing the steel when thickness of metal and length and width of members are considered.

6. The 10 columns of the Metropolis Bridge of Mayari, chrome, silicon, and carbon steel all failed in smooth curves, as against irregular failures of various types in the others. This is attributed to certain features of "compact" design and the type of lattice bracing used.

7. It is believed that column loads in practice should not exceed the proportional limit of the fabricated columns. The mean value of this proportional limit for the columns tested was 48.6 per cent of the maximum stress and 48.4 per cent of the tensile yield stress of the respective component steels.

8. The modulus of elasticity was taken as the ratio of the longitudinal stress to strain for values below the proportional limit of the columns. The value found from the mean of determinations on 15 columns was 29 600 000 ± 120 000. The closeness of this result to the mean value found for plain steel and to the results as found from tests of other large columns of a size commensurate with those of the investigation indicate that the methods used afford a reasonable calibration of the testing machine.

9. The ratio of lateral expansion to longitudinal compression was approximately that of plain steel. The range of variation observed was from 0.29 to 0.327 with an average of 0.30.

10. There was considerable evidence throughout the tests of some lack of elastic action in the "built-up" steel. Apart from the variations in the properties of the different shapes this is interpreted as due to (1) the unequal degrees of wrinkling in shapes while under stress, (2) a partial breaking down ultimately of the friction between surfaces of shapes as the load increases; and (3) the effects of initial strain induced by the driving of rivets.

11. The lowering of the "proportional limit" of a column below the elastic limit found in the compression of a test piece appears to be due in part to (1) the presence of initial strain induced by the radial pressure from the driving of the rivets, which unites with the direct stress from loading at a certain critical point of stress. The presence of these stresses are indicated not only by the theoretical considerations but also by supplementary tests on riveted and plain solid piece struts under compression loading; (2) a further cause is believed to be due to initial curvatures introduced in the elementary portions of the shapes between rivets as a result of the clamping action of riveters. The curvature in the elements which becomes sensibly apparent at a late stage of loading is believed to be one of the causes for

breaking down of the frictional resistances between plates and reducing the longitudinal shearing resistance. It is the opinion that fabricated steel should be studied in this connection with a view to raising the proportional limit of the column.

12. The action of the ordinary type of lattice bars in the body of the column is to draw together in the direction of column axis like a pantograph as the ribs shorten under load, the strains in lattice being small, such as occur being due to the slight resistance induced against bowing out of the flexible rib portions, as the lattice panels flatten out with the compression of the columns. The large strains are at those panels, close to end battens, where the restraint against the above uniform action causes more or less discontinuity of action, and produces bending in the ribs and a tendency to straining of inner edge of battens. The tendency of strong riveting at ends of lattice is to cause bending of lattice as the column ribs shorten, the stresses being largest in wide lattice bars. Column flexure proper apparently does not have much influence in members of small slenderness ratios, the more or less unsymmetrical distribution being due probably to readjustments in the bars themselves. The tendency of single lattice, on account of assymetry of the strain configurations induced, causes different curves of bending in the outer ribs, which in effect is equivalent to an eccentric application of the load on the column rib. The general tendency for these columns with the ordinary type of single and double lattice is to fail with irregular and local fractures. Symmetrical groupings of bars or component struts as far as possible operate advantageously.

13. The specific influence of transverse lattice bars between the panels is to prevent pantograph action of lattice bars, outward bowing of the ribs, and their abrupt bending at the batten plates and transverse diaphragms. It is the opinion that after the lattice has been designed for an arbitrary transverse shear taken as a safe per cent of the axial load to provide efficient trussing of the members for resistance against gravity and other transverse forces little advantage is gained by adding material to the intermediate diagonal bars. It should rather be placed in the transverse bars and ribs. The load on the column should be carried by the shortest path through the ribs alone, and not through ribs and lattice, as far as is practicable.

All the columns with transverse bars failed in smooth curves. This is regarded as favorable for maintaining the mechanical

principle of continuity, that the bending moment shall vary with the curvature of column, upon which correct principles of structural design are necessarily founded.

14. The tests showed that in nearly all cases the pin plates were long enough to give an easy transition of stress from the pin into the body of the web plates without buckling of the web plate at the end of the last pin plate. The pin plates appeared from the strain measurements to be of sufficient length to insure a quite uniform distribution of stress over the cross section before the web proper was reached. All the pin plates showed some relative slipping, which appeared to be due primarily to overstressing of rivets just over the pin on account of the intensity of stress at this point. This behavior, however, does not appear to reduce the column strength as a whole. There are, in fact, some grounds for believing that slipping of the pin plates or other portions relatively may at times have operated advantageously as an easement to adverse stress conditions. Many points of this nature can only be determined by independent tests on plain and laminated riveted steel. Tests of this character are recommended.

WASHINGTON, May 4, 1917.

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No. 102

PROPERTIES OF PORTLAND CEMENT HAVING A HIGH MAGNESIA CONTENT

BY

P. H. BATES, Chemist

Bureau of Standards

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I. INTRODUCTION

The question of the maximum amount of magnesia allowable in Portland cement is one of the most interesting encountered in the study of this complex material. There is as much diversity of opinion now as was shown by the committees of the German Portland Cement Manufacturers' Association appointed in 1891 and 1895 to investigate this subject. The committee of the latter year rendered majority and minority reports, the former considering magnesia in amounts not greater than 8 per cent harmless, whereas the minority considered amounts greater than 4 per cent injurious. The latter recommendation, strongly advocated by Dykerhoff, the chairman of the committee, was adopted. At present, however, 5 per cent magnesia is allowed by the German specifications.

Dykerhoff's recommendation having been so strongly opposed, further investigations were undertaken by the German association, but these were never finished; consequently no completed report was issued by this association covering its original program. The discussions continued, however, but excepting one of the last

investigations reported (Glasenapp, 1914 meeting) no very important data on this subject have been contributed.

All investigations to date have been at fault in that they did not take into consideration such important matters as the following: First, the history of the cements under investigation, particularly the kind and condition of the raw materials, the condition of firing, and the general characteristics of the clinker; second, the character and amounts of the constituents present in the clinker, especially as to how the constituents in clinker of low magnesia content have been changed in character and amounts by increasing magnesia content, and what new constituents, if any, have been produced; third, a sufficiently large number of cements with a gradual change in the magnesia content. The question has also been further involved by the use of magnesia added to ground cements in investigations which purported to be dealing with high-magnesia cements. Such, of course, can not be considered Portland cements.

Further investigations on this subject are needed because of the failures of mortars and concretes which have been attributed to such cements. The specifications under which cements are usually bought do not demand the making of test pieces of the material to be tested at late periods; but high-magnesia cements are generally conceded to be able to pass all the requirements demanded of the short-time tests. However, with the hydration of the compounds present in such cements it is claimed by some that there is a slow but gradual increase in volume, which is manifested at late periods by low results for the strength of test pieces and finally by complete disintegration of the material. While such cements may be satisfactory at early periods and pass the usual specifications, there is a strong belief in the minds of many that ultimately they will fail. As this phenomenon of the large increase in volume accompanying the slow hydration of the constituents in high-magnesia cements can be observed apparently only at late periods, it is essential to obtain some definite information in regard to this property, if it exists. It might be possible with this information to make definite predictions as to the ultimate behavior of such cements, even though short-time tests should show them to be satisfactory.

In the investigation herewith presented only those cements have been used which have been burned in the experimental rotary kiln of this Bureau (20 feet long by 2 feet in diameter) from raw

materials of which the character and fineness were known and at temperatures which were frequently determined during the burning and maintained constant within 25° C. The resulting clinker was carefully examined petrographically and the various constituents noted and their amounts quantitatively determined. Two series of burnings were made, the first consisting of the production of nine cements with a magnesia content ranging from 1.77 to 18.98 per cent, an average silica content of 22.31 per cent, and an average R_2O_3 (alumina plus ferric oxide) content of 10.32 per cent; and the second consisting also of nine cements with a lower average silica content (21.79 per cent) but higher average iron-alumina content (11.65 per cent) and a magnesia content ranging from 2.01 to 25.53 per cent.

Consequently, 18 different cements burned at as many different times were investigated. All of these were of normal composition except for the magnesia content. This procedure of having the high-magnesia clinker of approximately the same silica and R_2O_3 content as the low-magnesia clinker is open to some criticism, as, taking into consideration molecular proportions, the former should have had a higher silica or R_2O_3 content. Further burnings with this in mind are desirable, but the present investigation is confined to cements of usual composition.

It is not to be thought that this investigation was intended to show the desirability of increasing the amount of magnesia now allowed by the standard specifications. Its primary purpose was to determine what new constituents, if any, were produced in clinker by increasing the magnesia content, also how this latter increase affects the constituents already present, and, finally, to correlate the quantitative changes in the amounts of the various constituents with the changes which would be produced in the general physical properties of the cement.

II. RAW MATERIALS, THEIR PROPORTIONING AND BURNING

The analyses of the various materials used in preparing the "raw mixes" of the burns made are given in Table 1. These were proportioned in such a manner that, after burning and the addition of plaster of Paris and grinding, the cements have the composition shown in Table 2.

TABLE 1.—Analyses of the Raw Materials Used

	Clay	Lime-stone	Dolomite	Feldspar	Kaolin
	Per cent	Per cent	Per cent	Per cent	Per cent
SiO_2	60.07	0.08	0.17	70.83	45.86
Al_2O_3	20.37	.12	.11	16.60	37.56
Fe_2O_3	7.23		.10	.19	.52
CaO	.50	55.40	30.47	.44	.29
MgO	1.85	.79	21.43	.08	Trace.
Na_2O	.79	.....	.....	3.29	.37
K_2O	2.51	.....	.....	8.32	.63
Ignition loss	6.86	43.57	47.69	.63	14.79
	100.18	99.96	99.97	100.38	100.02

TABLE 2.—Analyses of the Various Burns

	Burn 16	Burn 25	Burn 26	Burn 27	Burn 28	Burn 29	Burn 30	Burn 31	Burn 32
	P. ct.	P. ct.	P. ct.	P. ct.	P. ct.	P. ct.	P. ct.	P. ct.	P. ct.
SiO_2	21.49	21.81	22.08	22.08	22.09	22.61	22.71	23.12	22.84
Al_2O_3	6.77	7.08	7.60	7.51	7.11	7.93	7.07	7.67	7.78
Fe_2O_3	2.88	2.57	2.69	2.94	2.77	2.82	2.96	3.31	3.41
CaO	64.54	62.68	61.37	60.16	59.60	56.88	55.54	48.00	44.09
MgO	1.77	3.27	4.20	5.12	6.49	7.41	9.50	14.07	18.98
SO_3	1.62	1.43	1.54	1.65	1.10	1.60	1.63	1.58	1.61
Na_2O	.07	.10	.10	.12	.14	.09	.15	.18	.28
K_2O	.34	.57	.32	.26	.30	.34	.34	.41	.52
Ignition loss	.52	.71	.38	.36	.61	.64	.46	1.35	.60
Total	100.00	100.22	100.28	100.20	100.21	100.32	100.36	99.69	100.11

	Burn 33	Burn 34	Burn 35	Burn 36	Burn 37	Burn 38	Burn 39	Burn 40	Burn 41
	P. ct.	P. ct.	P. ct.	P. ct.	P. ct.	P. ct.	P. ct.	P. ct.	P. ct.
SiO_2	22.35	22.33	22.11	21.76	21.53	21.39	21.38	21.22	21.60
Al_2O_3	8.95	8.32	8.79	8.50	8.32	7.85	8.36	8.46	8.15
Fe_2O_3	3.39	3.24	3.10	3.16	3.19	3.43	3.15	3.27	3.35
CaO	36.32	43.92	49.30	53.77	56.30	57.26	58.02	61.40	62.67
MgO	25.53	19.45	13.96	10.33	8.03	7.80	6.62	3.59	2.01
SO_3	1.43	1.73	1.83	1.61	1.62	1.67	1.62	1.56	1.63
Na_2O	.38	.00	.09	.13	.06	.09	.03	.00	.06
K_2O	.56	.16	.17	.27	.23	.38	.15	.16	.08
Ignition loss	1.01	.71	.68	.47	.59	.55	.61	.67	.42
Total	99.92	99.86	100.03	100.00	99.87	100.42	99.94	100.33	99.97

Burn 16 was made from a raw mix containing limestone, clay, and some feldspar (this latter was added to increase the silica somewhat without increasing the alumina to too great an extent, the ratio of silica to alumina in the feldspar being much greater than in the clay). In burns 25 to 32, inclusive, the raw materials were clay, limestone, and dolomite, but with the increasing serial number of the burns increasing amounts of the limestone were replaced with dolomite to give increasing amounts of magnesia. In burn 33 clay, dolomite, and kaolin were used (the latter to increase the alumina content over that obtainable with the clay alone). The same raw materials were used in burns 34 to 40, inclusive, but decreasing amounts of dolomite were replaced with limestone, until finally in burn 41, as in burn 16, limestone without any dolomite was used.

These raw materials, after having been crushed and passed through rolls until all passed a 10-mesh screen, were weighed out in the proper amounts and ground in a ball mill until 85 per cent passed a 200-mesh screen. They were then burned in a natural-gas-fired rotary kiln to such a temperature as produced a satisfactory clinker. In two cases (burns 25 and 26) an unfortunately low gas pressure did not allow of the production of the desired temperatures, with the result that there was obtained an underburned product. The average temperature of burning is given in Table 3. These temperatures were determined every 15 minutes by use of a Wanner pyrometer, which was sighted directly upon the clinker in the hot zone. As determined, they should be true to within $\pm 15°$ C. The use of natural gas in a kiln of this size permits of fairly accurate temperature determination.

TABLE 3.—Average Temperatures at which the Various Cements Were Burned

Burn No.	Per cent MgO	Degrees centigrade	Burn No.	Per cent MgO	Degrees centigrade	Burn No.	Per cent MgO	Degrees centigrade
15	1.77	1520	30	9.50	1497	36	10.33	1437
25	3.27	1430	31	14.07	1521	37	8.03	1423
26	4.20	1486	32	18.98	1499	38	7.80	1434
27	5.12	1512	33	25.53	1413	39	6.62	1450
28	6.49	1505	34	19.45	1410	40	3.59	1447
29	7.41	1530	35	13.96	1420	41	2.01	1446

In making burnings the kiln was gradually heated up to a rather bright red with gas burners using admixed air at atmospheric pressure. The burners were then changed to a type using air at a pressure up to 40 pounds per square inch. When the temperature with these had reached about 1250° C, the air was increased to such an amount that the gas no longer burned at the end of the burners but on the hot clinker. There was, consequently, no envelope of partially burning gases interfering with the direct sighting of the pyrometer on the clinker, and it was, furthermore, possible to sight directly on the hottest clinker, the latter in the hot zone being also hotter than any part of the kiln.

An examination of Table 3 in connection with Table 2 shows the effect of the increase of the alumina-iron oxide content and the decrease in the silica content in lowering the temperature of clinkering. But it does not appear that the increased amounts of magnesia have produced the decrease in clinkering temperature that would be expected. But while the clinkering temperature was not reduced very appreciably, yet the indications are that the "softening point" was decidedly reduced. In cement-manufacturing practice the proper clinkering temperature is the lowest temperature at which the lime will combine with the clay (or other argillaceous material) to such an extent that the ground clinker will produce both a sound cement and one containing but a small amount of insoluble material.[1] Usually this temperature is decided entirely by the appearance of the clinker, and invariably this serves all purposes, though it may happen that a very vitreous clinker may contain so much free lime that the resulting cement may not be sound.[2] In the present case the high-magnesia raw mixes gave clinker that, when burned at the proper temperature as judged by the appearance, "dusted"[3] in a very short time (5 to 30 minutes, depending upon the rate of cooling). If the temperature was increased until a decidedly overburned or very hard clinker was obtained, "dusting" again resulted. At a temperature somewhat lower than the latter a clinker was obtained that showed minimum immediate "dusting," though it slowly changed to the powdered condition. Therefore, the temperatures as shown in Table 3, at which the higher-magnesia cements were burned, are

[1] U. S. Government Specifications for Portland Cement. Bureau of Standards Circular No. 33. Paragraphs 2 and 29 and "Insoluble Residue" under II.

[2] There is in the Pittsburgh branch of the Bureau a piece of very hard vitreous clinker that has been exposed to the air for three years without signs of slaking and yet contains so much free lime that the cement made from it is decidedly unsound.

[3] Change of the β orthosilicate of lime ($_2CaO.SiO_2$) to the γ form, with accompanying increase in volume of almost 10 per cent.

the temperatures that are decidedly beyond those required to combine the basic and acidic components, but are the temperatures that gave the maximum amounts of satisfactory clinker. In Fig. 1 is shown the progressive "dusting" of burn 33 at the end of 30 minutes, and 24 hours after dropping from the kiln. This continued for a period of about a year, when equilibrium seemed to have been reached.

This slow "dusting" was not noted in any of the burns containing less magnesia than that shown by No. 30 (9.50 per cent); but to prevent this phenomenon in these cases a higher temperature was used than that actually required to bring about combination of the basic and acid components of the mix. It is well known that in such mixtures as used in making Portland cement an increase of magnesia lowers the softening point of the mixture. In usual cement-mill practice, where complete analyses of the raw mixes are not made frequently, and where the magnesia content may reach a fairly high amount, the latter condition is first noted in the kiln by a decided tendency of the clinker to "ball" or form "logs," due to the lowering of the softening point.[4]

The whole phenomenon of "dusting," or the changing of the beta form of the orthosilicate of lime to the gamma form, is worthy of attention and further investigation. Low-burned or very slowly cooled clinker may contain the latter form. Well-burned clinker of the proper composition or clinker which has been rapidly cooled through the inversion point of the beta to the gamma form (675° C) will not contain it. But, as noted above, the beta form in certain instances does gradually change to the gamma form very slowly and over long periods. As this change is accompanied by an increase in volume of 10 per cent, it can readily be seen what damage would be produced in a concrete if this change should take place after the clinker has been ground and made into a concrete. It would be well, therefore, when examining disintegrated concrete to look for the gamma form of orthosilicate.

With marked increase in magnesia content the difficulties of burning increased considerably. This was very marked when the percentage of magnesia was increased beyond 9.5 per cent. When the amount was less than this, the clinker was both approximately normal in appearance and normal in its behavior in the kiln, giving the usual black glistening cokelike material, which rolled about in the kiln without any tendency to form large balls or "logs" or

[4] "High Magnesia Cements." Discussion by Prof. Glasenapp, Mitt. der Central. zur Forder. der Deutch. Port. Cement Ind., 4, pp. 58–62.

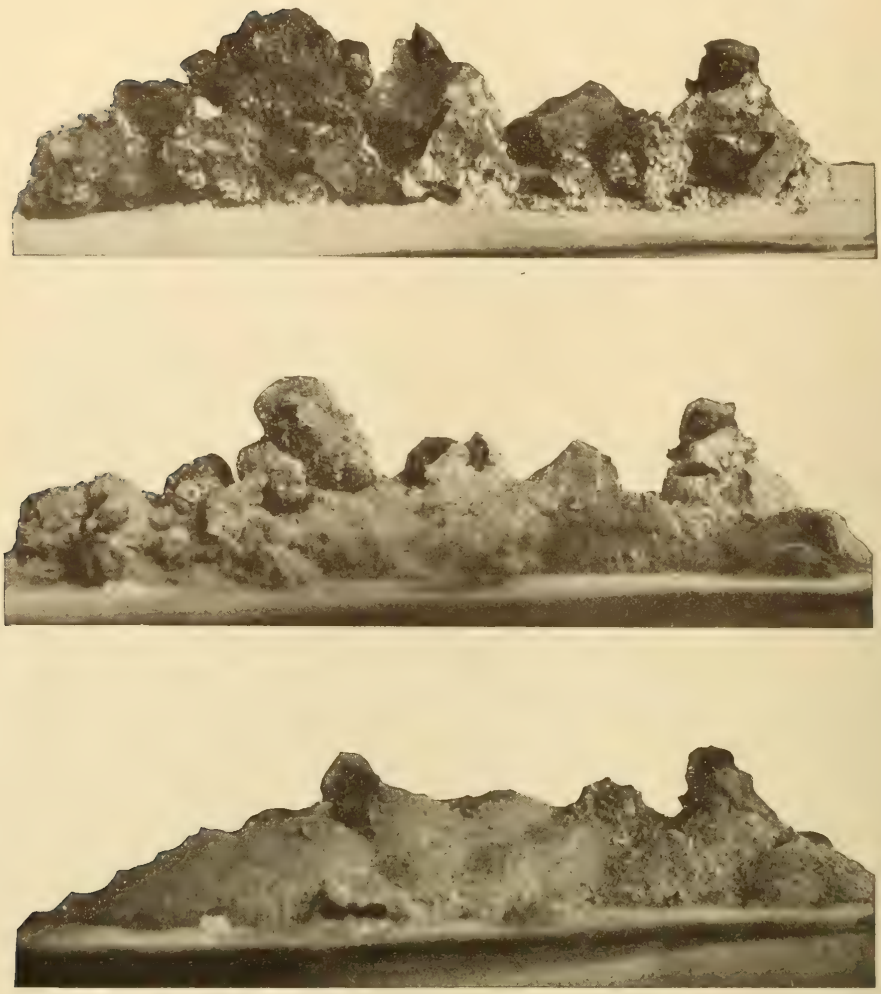

FIG. 1.—*Clinkers from burn 33*

Top, hot clinker; middle, same clinker at end of half hour; bottom, same clinker at end of 24 hours. This shows the inversion of the beta to the gamma orthosilicate, accompanied by a large increase in volume. This phenomenon is usually referred to as dusting of the clinker

to "ring up." When this amount was exceeded, the clinker was of a reddish-yellow appearance, which gave a considerable amount of an ochrelike dust and a yellow cement, the latter giving a yellow, muddy, plastic concrete. The formation of rings was also excessive.

III. PETROGRAPHY OF THE CLINKER

One of the main reasons for making this investigation was to determine the constitution of the clinker and to note in particular the changes produced in clinker of low magnesia content by the replacement of increasing amounts of lime by magnesia. Klein and Phillips [5] in this laboratory were among the first to make a study of this matter in the light of the present exact data of the Geophysical Laboratory.[6] According to the results of Klein and Phillips, magnesia could exist in Portland cement in amounts as great as 7.5 per cent before there would appear a new compound not present in ordinary clinker; that is, below this amount it would form homogeneous compounds with either the beta orthosilicate or the tricalcium aluminate. Some doubt has been thrown upon their results, however, by Rankin,[7] who found that in the compound $3CaO.Al_2O_3$, in which 10 per cent of the lime had been replaced by magnesia, the latter was present as free magnesia, whereas Klein and Phillips found a homogeneous compound with a lower refractive index than that which the tricalcium aluminate has. However, a reexamination of this preparation failed to show any free magnesia, but it does contain appreciable amounts of silica and possibly a few tenths of a per cent of iron oxide. In the preparation approaching the composition of Portland cement but with high magnesia content they could not detect any free magnesia.

In the present investigation the constituents noted were those present in cement of normal composition and proper burning, namely, tricalcium silicate ($3CaO.SiO_2$), three forms—β, β', and γ—of dicalcium silicate or orthosilicate of lime ($2CaO.SiO_2$), and tricalcium aluminate ($3CaO.Al_2O_3$). When the percentage of magnesia reached about 8 per cent, monticellite ($MgO.CaO.SiO_2$) was noted; with a slightly greater percentage, spinel ($MgO.Al_2O_3$) appeared; and, finally, in the two burns of highest magnesia content

[5] Klein and Phillips, "Magnesia in Portland Cement," 8th Int. Cong. Appl. Chemistry, 5, p. 73.

[6] Rankin, "The Ternary System, $CaO.Al_2O_3.SiO_2$," Amer. Jour. Science, 39, No. 229; Jan., 1915. Rankin and Merwin, "The Ternary System, $CaO–Al_2O_3–MgO$." Jour. Amer. Chem. Society, 38, No. 3, p. 568. Jesser, "Magnesia in Portland Cement," Tonind. Zeitung., Oct. 21, 1911.

[7] Rankin, "The Constituents of Portland Cement Clinker," Jour. Ind. & Eng. Chem., 7, No. 6, p. 466, June, 1915; "The Ternary System, $CaO–Al_2O_3–MgO$," Jour. Amer. Chem. Soc., 38, No. 3, p. 568.

some free magnesia was noted. The constituents which are characteristic of the high-magnesia cements are, therefore, monticellite, spinel, and, of much less importance, free magnesia.

An attempt was made to determine quantitatively the percentage of constituents present in each of the burns. This was done by preparing thin sections of characteristic clinker of each burn. To avoid possible action of water during the grinding of the sections, they were ground in a nonsaponifiable oil, and immediately after being reduced to a satisfactory thinness were covered with a cover glass and sealed with balsam from all possible action of atmospheric moisture. These were then examined in the petrographic microscope in the following manner: Instead of the ordinary Huyghenian ocular a positive Ramsden ocular was used. This was fitted to a holder containing a slot in which a double-coordinate plate was inserted. The objectives used were the 4 mm and the 8 mm, depending upon the fineness of the individual grains, the former being used for the finer grains. The amount of the various constituents in a field was estimated in terms of the smallest square divisions of the double-coordinate plate, which covered an area in actual size of 0.00178 ± 0.00006 mm square with the 4 mm objective and 0.00385 ± 0.00025 mm square with the 8 mm objective. At least 20 fields taken at random, but including all parts of the thin section, were so integrated. The sum total of the constituents in terms of their units of area was obtained by adding the respective values for the individual fields, and these results were calculated to 100 per cent. These are shown in Table 4.

Such a method, of necessity, is only approximately quantitative, and it is rendered more inaccurate by the impossibility of distinguishing, in thin sections, between tricalcium silicate or tricalcium aluminate or spinel. Consequently, in the foregoing table these three constituents appear together. It is possible, however, to form an idea of the relative amount of tricalcium silicate present by bearing in mind that all the alumina is combined either as the tricalcium aluminate or spinel and that the latter appears only in the burns containing 9.5 per cent or more magnesia, increasing therefrom very slightly with increasing magnesia percentages. The results show, however, how the amount of β orthosilicate decreases with increased amounts of magnesia. Apparently, therefore, the monticellite, which increases with increased amounts of magnesia, has been formed at the expense of the orthosilicate. It is also evident that the

amount of tricalcium silicate has not been materially reduced. The β' orthosilicate was noted in some cases in small amounts, usually only in the presence of the greater amounts of magnesia. (In other work by this laboratory its presence has been noted in high-alumina cements.)

TABLE 4.—Petrographic Analyses of the Various Burns

Burn No.	Percentage MgO	Percentage of the various constituents					
		Tricalcium silicate, tricalcium aluminate, spinel [a]	β Calcium orthosilicate	"Ferrite"	Monticellite	Spinel	Free lime
16	1.77	61.6	30.6	7.6	None	None	Trace
25	3.27	38.9	47.0	10.4	None	None	3.7
26	4.20	43.2	45.3	9.1	None	None	2.4
27	5.12	51.8	39.6	8.2	None	None	.5
28	6.49	47.9	41.6	9.0	None	None	1.5
29	7.41	49.8	40.3	9.9	None	None	Trace
30	9.50	54.1	35.7	10.2	[b] Present	None	None
31	14.07	56.0	[c] 32.4	8.3	2.2	Present	None
32	18.98	57.1	20.7	7.8	11.5	Present	None
33	25.53	52.0	[d] 13.5	11.3	23.2	Some	None
34	19.45	53.2	[e] 20.7	8.9	17.2	Some	None
35	13.96	46.8	[f] 26.9	11.4	14.9	Little	None
36	10.33	50.6	29.8	10.5	9.1	Very little	None
37	8.03	51.2	35.8	9.7	4.3	None	None
38	7.80	53.0	37.2	8.9	.9	None	None
39	6.62	54.3	36.6	9.1	None	None	None
40	3.59	55.7	35.8	8.5	None	None	None
41	2.01	56.2	33.5	9.9	None	None	Trace

[a] See text for the reason of this grouping.

[b] Present in such small quantities and so poorly developed as not to be distinguishable from the β orthosilicate in thin sections.

[c] β' orthosilicate present (about 1.1 per cent).

[d] β' orthosilicate present (about 3.7 per cent).

[e] β' orthosilicate present (about 2.1 per cent).

[f] β' orthosilicate present (about 1.7 per cent).

The appearance of the structure of the clinker of these cements is very characteristic, there being a remarkable tendency to the formation of large grains and crystals. The formation of the tricalcium silicate in the presence of large amounts of magnesia is very similar to its formation in the presence of large amounts of alumina. In both cases it tends to crystallize in large well-defined needles. This tendency is, however, not restricted to either of these classes of cements alone, as both burns 40 and 41 exhibited this characteristic and are neither high-magnesia nor high-alumina cements, but this tendency is more marked than

with cements of normal composition. As will be seen later, this formation of large grains plays an important part in the properties of these cements. In Figs. 2 to 6 are shown a number of photomicrographs of thin sections of the cements used in this investigation, examined both with and without crossed nicols. In these the distinct granularity of the major constituents may be particularly noted.

IV. PROPERTIES OF THE CEMENT

1. TIME OF SET

The clinker, without either quenching or storing, was crushed in jaw crushers, passed through rolls until all passed a 20-mesh screen, and after the addition of approximately 3 per cent of plaster was ground in a porcelain-lined ball mill to the fineness shown in Table 5. Without any storage or aeration, the ground cement was then tested for time of set, constancy of volume, and strength in the form of neat tension and 2-inch-cube compression briquettes, 1:3 Ottawa-sand tension and 2-inch-cube compression briquettes, and 6-inch 1:1½:4½ gravel-concrete cubes.

TABLE 5.—Fineness and Soundness of the Different Cements

Burn No.	Per cent passing sieve		Pats subjected to—			
	100-mesh	200-mesh	Boiling water	Steam	28 days in air	28 days in water
16	96.0	79.6	O. K.	O. K.	O. K.	O. K.
25	99.2	75.8	Disintegrated	Disintegrated	O. K.	O. K.
26	98.4	79.8	Disintegrated	Disintegrated	O. K.	O. K.
27	97.6	78.6	O. K.	O. K.	O. K.	O. K.
28	99.0	77.6	O. K.	O. K.	O. K.	O. K.
29	97.2	76.0	O. K.	O. K.	O. K.	O. K.
30	92.0	73.2	O. K.	O. K.	O. K.	O. K.
31	95.4	79.0	O. K.	O. K.	O. K.	O. K.
32	97.2	90.4	Soft and cracked.	Soft and cracked.	O. K.	O. K.
33	97.0	81.4	Soft	Soft	Warped	O. K.
34	94.4	76.9	O. K.	O. K.	O. K.	O. K.
35	94.9	79.2	O. K.	O. K.	O. K.	O. K.
36	96.4	78.8	O. K.	O. K.	O. K.	O. K.
37	95.6	78.4	O. K.	O. K.	O. K.	O. K.
38	97.4	79.0	O. K.	O. K.	O. K.	O. K.
39	97.8	80.1	O. K.	O. K.	O. K.	O. K.
40	97.0	78.0	O. K.	O. K.	O. K.	O. K.
41	96.6	78.6	O. K.	O. K.	O. K.	O. K.

FIG. 2.—*Photomicrographs of a thin section of clinker of burn 40*

Shows the development of long crystals of the tricalcium silicate. Top examined in plane-polarized light; bottom examined with the nicols crossed. This development of the tricalcium silicate was very marked in the burns in this investigation, being more noticeable in those containing higher percentages of magnesia. It is characteristic of well-burned commercial clinkers containing considerable fluxing material. Magnified 275

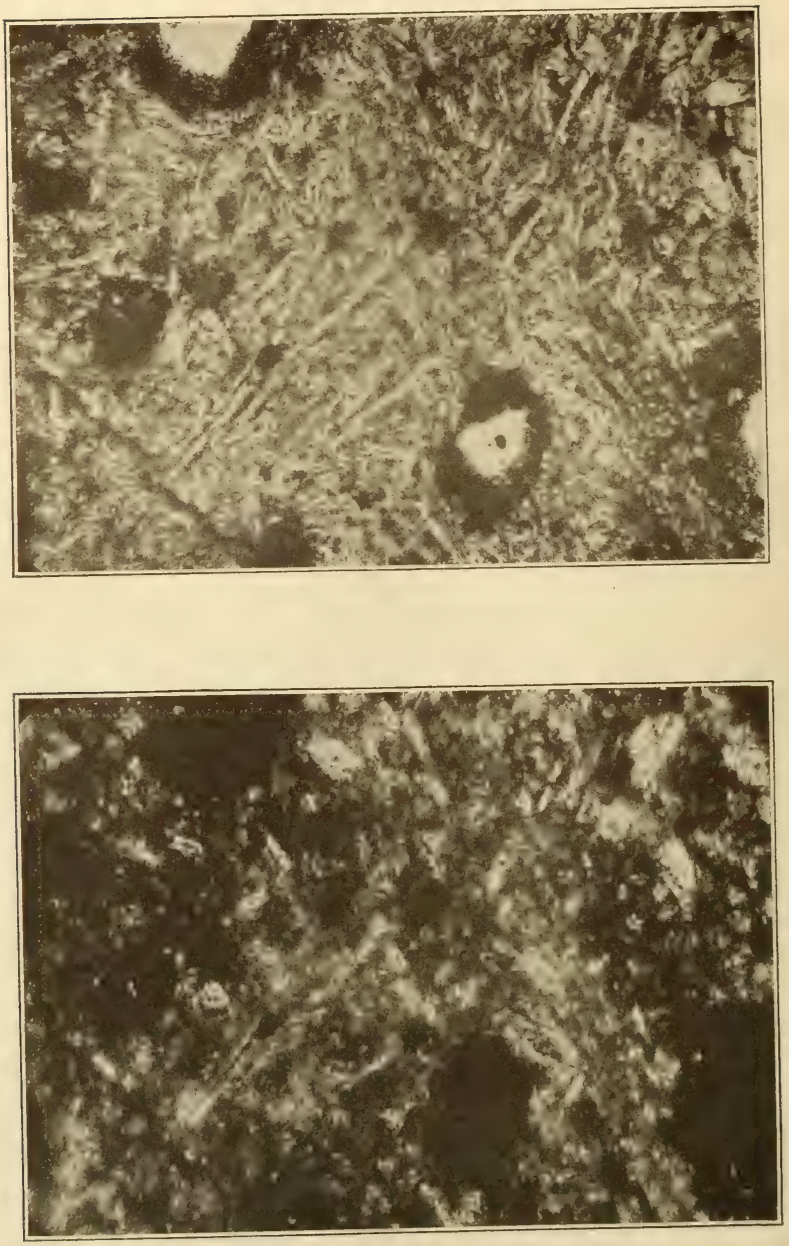

FIG. 3.—*Photomicrographs of a thin section of clinker of burn 37*

Also shows the development of long crystals of tricalcium silicate embedded in the orthosilicate. Top examined in plane-polarized light; bottom examined with the nicols crossed. (See remarks under Fig. 2.) Magnified 275

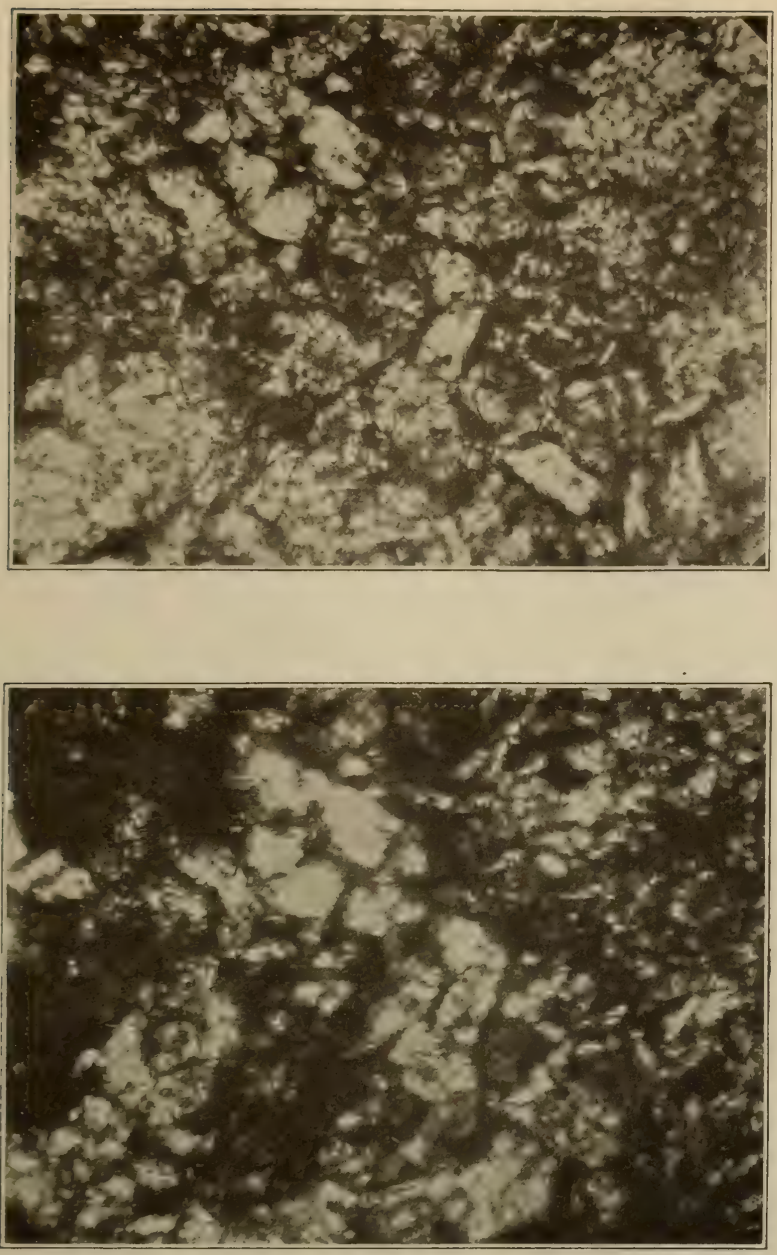

FIG. 4.—*Photomicrographs of a thin section of clinker of burn 33*

Some of the larger well-defined grains are monticellite embedded in the orthosilicate; others are tricalcium silicate. Top examined in plane-polarized light; bottom examined with crossed nicols. Monticellite is a characteristic constituent of clinker high in magnesia. Magnified 275

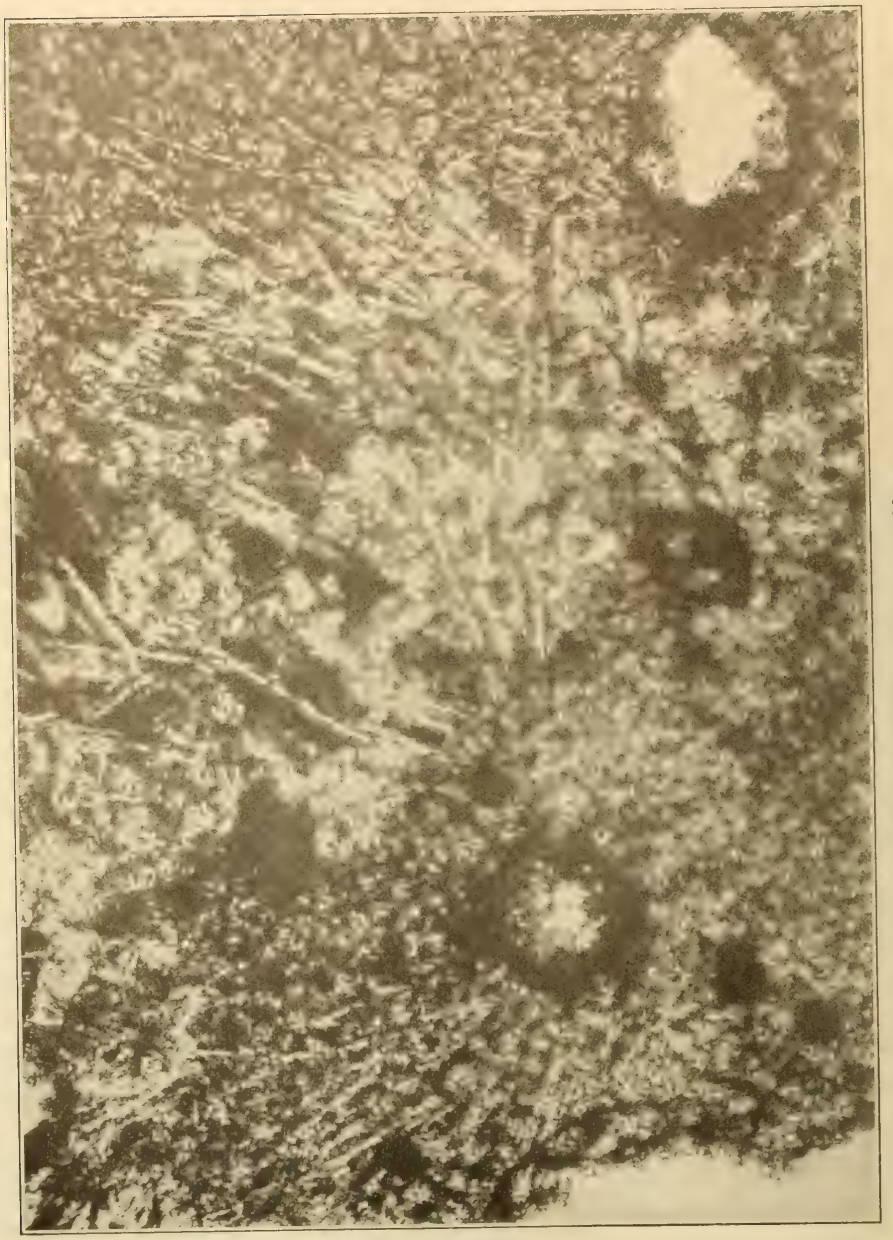

FIG. 5.—*Photomicrograph of burn 37*

Shows an area of very large elongated crystals of tricalcium silicate embedded in the orthosilicate. This shows how the constituents in a clinker are not uniformly distributed throughout the mass. This is characteristic also of commercial clinker. Magnified 275

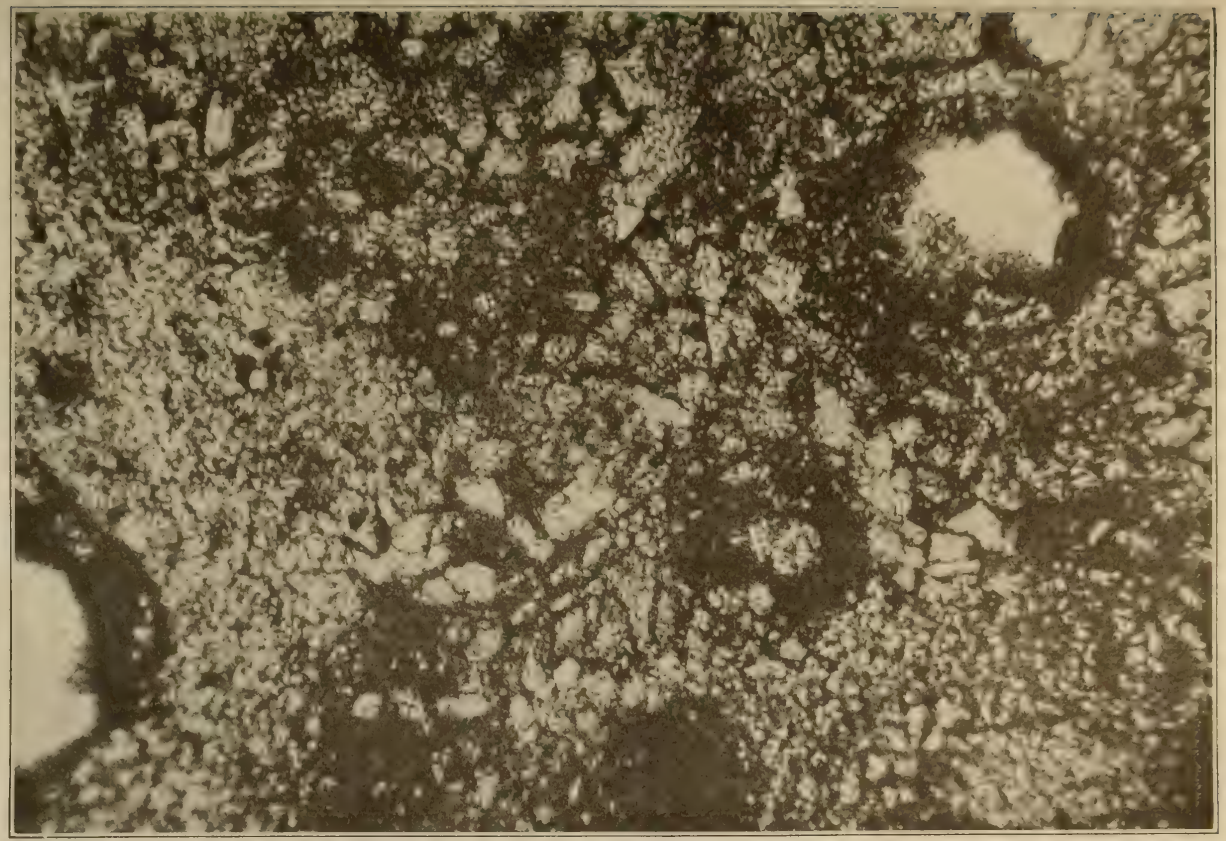

FIG. 6.—*Photomicrograph of burn 33*

The white grains are either monticellite or tricalcium silicate; the dark ground is largely the orthosilicate. There is also spinel present but it can not be distinguished from the monticellite or tricalcium silicate in the photomicrograph. Magnified 220

The normal consistency, time of set, and specific gravity of the finished cements are shown in Table 6. It can be seen from this table that there is no marked change in the time of set until the percentage of magnesia approaches 10 per cent. At this amount there is a tendency toward quick setting, especially in the development of a quick initial set and an apparently quick final set. The latter, however, can hardly be called a true final set, but is really a rapid drying out of the test piece due to the excessive heat evolved by the very early hydration. This evolution of heat was so marked that the test pieces gave off steam in the cases of burns 31, 32, 34, and 35. In the case of burn 33 the heat evolved was not so marked. The time of set shown for burn 32 was not the true time, since in order to obtain a test specimen an excessive amount of water was used, which undoubtedly masked a "flash" or an almost instantaneous set. Burn 33 also gave a "flash" set.

TABLE 6.—Time of Set, Consistency, and Specific Gravity of the Various Cements

Burn No.	Per cent MgO	Normal consistency	Time of set								Specific gravity
			Vicat				Gilmore				
			Initial		Final		Initial		Final		
			hrs.	min.	hrs.	min.	hrs.	min.	hrs.	min.	
16	1.77	20.0	0	55	6	40	3	00	8	05	3.192
25	3.27	21.0	2	15	6	10	3	05	8	30	3.157
26	4.20	20.5	2	15	7	30	3	45	9	15	3.200
27	5.12	19.0	2	40	6	15	4	00	8	30	3.234
28	6.49	21.0	1	35	5	10	2	35	6	30	3.216
29	7.41	20.5	1	20	6	30	4	25	9	00	3.259
30	9.50	19.0	1	00	9	30	3	20	13	00	3.243
31	14.07	18.0	[a] 1	05	[a] 1	25	[a] 0	06	[a] 2	05	3.225
32	18.98	31.0	[a] 1	00	[a] 30	00	[a] 5	00	[a] 48	00	3.178
33	25.53	18.5	[b] 0	30	[b] 25	00	[b] 4	00	[b] 48	00	3.275
34	19.45	24.0	[a] 0	05	[a] 0	15	[a] 0	10	[a] 1	30	3.225
35	13.96	24.5	[a] 0	05	[a] 0	12	[a] 0	08	[a] 1	25	3.110
36	10.33	18.5	1	30	3	30	2	00	4	00	3.240
37	8.03	19.0	2	10	5	00	3	15	5	50	3.230
38	7.80	19.0	2	20	4	10	3	05	5	00	3.224
39	6.62	19.5	1	55	4	15	3	35	5	25	3.200
40	3.59	19.5	1	35	4	00	2	10	4	45	3.193
41	2.01	19.5	1	35	5	00	2	05	5	40	3.205

[a] All test pieces became quite warm, especially the Vicat. [b] Flash set (?), see text.

Unless the relative amounts of the various constituents of the cement were known, and also their characteristic formation—distinctly granular and distinctly separated from one another—it

would be extremely difficult to explain the rôle of magnesia in making the cement quick-setting. An examination of Table 4 shows that the amount of the orthosilicate of lime has rapidly decreased when the magnesia was increased beyond 7.5 per cent; further, the amounts of tricalcium silicate, tricalcium aluminate, and spinel have remained approximately constant; and while the amount of spinel did increase with increased magnesia, yet it was very small at all times. Consequently the amount of the quickly hydrating compounds (tricalcium silicate and tricalcium aluminate) has increased considerably when compared with the amount of slowly hydrating material (orthosilicate of lime). As a consequence, the high-magnesia cement must of necessity develop a very quick set and one accompanied by the evolution of a large amount of heat.[3]

This quick hydration and setting takes place with this class of cements, notwithstanding the presence of the relatively large amount of monticellite. This latter material can be considered as not hydrating, at least within the course of several months. Furthermore, it is not present in the cement in the same manner as the orthosilicate. This latter does not occur in large well-defined grains like the former, but more like a fused mass surrounding the grains of the other constituents, and after crushing it may still in a measure cover these and prevent the water rapidly reaching them on account of its very slow hydration. It can readily be seen, therefore, how the structure and constitution of the high-magnesia cements should produce rapid setting.

2. CONSTANCY OF VOLUME

The constancy of volume was determined by subjecting the pats of the usual form, 24 hours after making, to an atmosphere of steam for 4 hours at atmospheric pressure, to storage in air for 28 days, to storage in water for 28 days, and to storage in boiling water for 4 hours. The pats showed soundness except in the following cases: Burns 24 and 25 showed bad disintegration when subjected to steam and boiling water, burns 32 and 33 were soft when subjected to steam and boiling water, and burn 33 showed a slight warping when subjected to air storage for 28 days. As stated before, the first two burns mentioned above were, owing to low gas pressure, distinctly underburned. Burns 32 and 33, however,

[3] Klein and Phillips, "The Hydration of Portland Cement," Technologic Paper No. 43, Bureau of Standards. It has been found in the laboratory when large amounts of pure tricalcium aluminate (1 kilo) are mixed with water, in the proportion of two of the former to one of the latter, the heat evolved raises the mass beyond the boiling point of water.

were really not set when subjected to the boiling and steam treatment, and undoubtedly burn 33 showed warping of the pat stored in air for the same reason of slow set, having dried out and warped before it set.

Some of these cements were subjected to a more quantitative test for their constancy of volume. Duplicate bars of 1:1½:4½ gravel concrete (5 by 5 by 45 inches) were made of these cements, and at the end of 24 hours an initial measurement of a gauged length (approximately 39 inches) was made. They were then removed from the form and one bar allowed to remain indoors subjected to the air of the laboratory. The other bar was kept for one week under wet burlap, and then, having gained sufficient strength to permit of handling, was placed in water. Subsequent readings of changes in length were made at various periods. The results are shown in Table 7. It was not possible to secure bars of the very high-magnesia cements, all bars made having been broken in handling owing to their very low early strength.

The measurements at the various periods were made with an extensometer made of two parallel ¾ by ¾ by 42 inch oak rods, joined at the ends and at two equidistant points between with pieces of oak of the same cross section. Through one of the end cross rods there was securely fastened a steel set screw and on the other an Ames dial graduated to 0.001 mm. In making measurements the set screw was brought up against the outer side of one of the copper gauge points placed in the concrete, which projected about ½ inch above the concrete, and then the spindle of the Ames dial brought against the outer side of the other gauge point. The reading of the dial was then noted and could be checked to 0.003 mm. Immediately after making the reading the distance between the end of the spindle and the end of the set screw was determined with a microscopic comparator. All readings are corrected to 20° C, using 0.000009 and 0.0000108 as the temperature coefficients of expansion of concrete and steel, respectively.

This table (7) shows that the high-magnesia cements produce concrete showing a similar deportment, so far as expansion is concerned, to concrete made from cements of normal composition. They show usually contraction when stored in air and expansion when stored in water, but it does not appear that the magnitudes of these changes are consistently greater when the cement contains a large amount of magnesia. It should further be noted that this change is greater in the later burns in which the silica-

TABLE 7. Expansion (in Per Cent of Original Length) of 1:1½ : 4½ Concrete Bars

[Unless otherwise noted, expansion in air is negative and in water positive. Reduced to 20° C.]

Burn No.	Per cent MgO	Stored in	1 week	2 weeks	1 month	2 months	3 months	4 months	6 months	9 months	12 months	15 months	19 months	23 months	29 months	35 months
19	1.77	Air	0.031	0.014	0.018	0.024	0.019	0.032	0.036	0.044	0.044	0.039	0.038	0.035	0.039	0.040
		H_2O	.007	.020	.026	.039	.067	.054	.058	.062	.064	.064	.065	.055	.051	.055
25	3.27	Air	.007	.013	.023	.019	.006	.....	.011	.015	.017	.016	.014	.009	.009	.010
		H_2O	.003	.046	.042	.086	.134	.195	.194	.195	.196	.197	.203	.199	.196	.188
26	4.20	Air	.019	.022	.033	.036	.048	.053	.052	.052	.063	.063	.067	.063	.054	.053
		H_2O	− .010	− .000	− .001	− .006	− .002	.....	− .007	− .005	− .028	− .018	− .012	+ .037	.066	.079
27	5.12	Air	.017	.032	.035	.043	.038	.044	.056	.063	.069	.060	.070	.....	.....	.....
		H_2O	.009	.012	.027	.029	.027	.038	.030	.038	.032	.042	.058	.053	.047	.047
28	6.49	Air	.008	.017	.019	.018	.045	.043	.045	.051	.054	.051	.054	.050	.044	.047
		H_2O	.003	.013	.022	.032	.033	.036	.034	.039	.047	.050	.048	.047	.044	.041
29	7.41	Air	.016	.035	.044	.038	.048	.047	.048	.051	.051	.053	.....	.055	.064	.064
		H_2O	− .001	.011	.010	.021	.007	.011	.017	.018	.028	.024	.019	.....	.071	.081
30	9.50	Air	.017	.033	.039	.057	.071	.071	.074	.078	.077	.079	.074	.070	.076	.075
		H_2O	− .005	.009	.003	.005	.012	.012	.017	.015	.025	.022	.033	.047	.077	.084
31	14.07	Air	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
		H_2O	− .027	− .061	− .038	− .032	− .008	− .002	− .013	.017	.010	.006	.004	.003	.007	[a].005
36	10.33	Air	.058	.058	.059	.073	.082	.090	.084	.085	.092	.092	.087	.100	.089	.095
		H_2O	− .009	.000	.005	.008	.009	.010	.027	.033	.033	.053	.056	.073	[a]	[a]
37	8.03	Air	.028	.032	.043	.049	.055	.057	.057	.058	.064	.060	.064	.063	.062	.064
		H_2O	− .022	− .023	− .017	− .008	− .003	.008	.013	.022	.014	.035	.033	.041	.060	.074
38	7.80	Air	.015	.015	.014	.017	.022	.027	.023	.023	.035	.034	.029	.033	.033	.033
		H_2O	.007	.025	.044	.050	.051	.....	.056	.061	.061	.070	.078	.087	.092	.097
39	6.62	Air	.005	.031	.039	.038	.058	.068	.058	.059	.061	.061	.061	.062	.059	.065
		H_2O	.031	.045	.045	.042	.045	.034	.064	.090	.089	.104	.094	.096	.095	.100
40	3.59	Air	+ .021	+ .017	+ .012	+ .006	+ .002	− .001	.....	+ .006	+ .000	− .002	− .010	− .012	.012	.012
		H_2O	.045	.052	.057	.058	.057	.056	.061	.068	.076	.081	.....	.....	.....	.....
41	2.01	Air	.052	.056	.057	.061	.068	.067	.061	.068	.070	.075	.081	.086	.078	.077
		H_2O	− .008	.000	.002	.006	.004	.004	.....	.010	.007	.009	.....	.001	.006	.004

[a] These bars are expanding unequally on the top (exposed to damp atmosphere during the first 24 hours after making) and on the bottom (resting on the bottom of form in which it was cast during the first 24 hours). This causes a curving of the bar, which may result in the readings showing a contraction, since they are made on the side showing little or no expansion.

alumina ratio was a little lower than in those (burns 33–41) in which the ratio was greater. It would appear somewhat as if the alumina content affected the volume changes as much as the magnesia content. However, there were not a sufficient number of test pieces, neither are the readings sufficiently accurate, nor was it possible to control either the humidity of the specimen stored in air or the many other variables which naturally affect these measurements, to make the results much more than qualitative.

Attention should also be called to the measurements made on burns 25 and 26. These, as noted before, were unsound according to the boiling and steaming tests for constancy of volume. The concrete from burn 25 shows that it has contracted less in air and expanded more in water than the other cements, showing thereby that it is acting as an unsound cement usually does. However, as a concrete specimen, when examined macroscopically, it appears perfectly normal at the end of two and one-half years. Burn 26 shows a large contraction in air and a contraction also in water over a rather extended period, as shown in the table. After a year the contraction changed to an expansion, and the latter is now continuing very rapidly, as found by later measurements. All the results show the difference in concretes made from different cements, although it is undoubtedly premature to say that differences in the coefficient of expansion of various concretes are due to the use of a different cement. The cement is but one of the many variables in this very complex material, and it is possible to conceive that differences in consistency and amount of tamping would allow of very great differences in this coefficient, though in the present case these were kept as uniform as possible.[9]

3. STRENGTH OF NEAT, MORTAR, AND CONCRETE TEST PIECES

The different test pieces made for the determination of the strengths developed by the various cements were (*a*) neat-tension briquettes and 2-inch compression cubes; (*b*) tension briquettes and 2-inch compression cubes of 1:3 standard Ottawa-sand mortar; (*c*) 6-inch compression cubes of 1 : 1½ : 4½ gravel concrete.

For some unknown reason cements with a high-magnesia content have been considered readily susceptible to the action of sea water. For some time specifications for Portland cement

[9] See Taylor ("The Elasticity of Compound Bars with Special Reference to Reinforced Concrete Columns," Concrete and Constructional Eng. 9, No. 12, p. 722; 1914) for a striking presentation of the various values obtained for the coefficient of expansion of concrete.

used very widely limited the amount of magnesia to 3 per cent when the cement was to be used in contact with sea water, while allowing 4 per cent when used for all other purposes.

How this prejudice against high-magnesia cements arose is a question. The usual explanation given is that it was found that cements which had failed in sea water contained a large amount of magnesia. But it is never stated sufficiently definitely whether this magnesia was in the cement before it was placed in sea water or was found there after it had been in contact with the water. If the latter was actually the case, there is no reason to assume that the cement was originally high in magnesia, as the first effect of placing cement in sea water is the reaction between the lime freed from the cement by the water and the magnesia salts in solution, resulting in the solution of the lime and the deposition of the magnesia. The solution by sea water of the lime freed from Portland cement is an expected and normal action, and it must be accompanied by the deposition of magnesia from the sea water.

In view of this prejudice against high-magnesia cements, it was decided to determine the effects of salts in solution on concrete made from the cements used in this investigation. Sea water, however, was not used on account of its inaccessibility and also because previous work of this laboratory [10] had shown that certain of the salts present in sea water had a greater destructive force on concrete when present in a different concentration than in sea water. Also, it had been found that alternate wetting and drying of the concrete produced the maximum destruction in the least time. Consequently, one set of the test pieces was stored for various alternate periods in air and in a 2 per cent solution of equal parts of crystallized sodium chloride, sodium sulphate, magnesium chloride, and magnesium sulphate. The cubes tested at the end of 28 days had been stored alternately in the solution and in air for four periods of one week each. Those tested at 90 days had the same storage as those tested at 28 days and in addition three periods of one week each in the solution with intermediate drying in air for one-week periods. The 26-week test pieces had the same treatment as the 90-day ones, plus an additional storage in the solution of two three-week and one four-week periods with intermediate dryings between each of these periods of one week in air. All remaining test pieces were given the same

[10] Bates, Phillips, and Wig, "The Action of the Salts in Alkali Water and Sea Water on Concrete," Bureau of Standards Technologic Paper No. 12.

treatment as the 26-week ones, but were further stored in the solution for periods of four weeks each with intermediate dryings of two weeks each until the end of one year, when all were removed and stored in air.

Another set of the concrete cubes was stored in tap water for the same periods of wetting and placed in air for the same periods of drying as the test pieces stored in the solution. This second set served as a standard with which to compare those stored in the solution. Concrete cubes were also made of some of the cements which, after 24 hours in a damp atmosphere, were stored constantly in the air of the laboratory. All neat and mortar test pieces were stored continuously in water after the first 24 hours in the damp closet.

(*a*) *Neat Test Pieces.*—The strengths developed by the neat specimens are shown in Table 8, these being the average for three test pieces. It is clearly seen from these that an amount of magnesia of approximately 7 per cent can be reached before there is a noticeable falling off in the strength of this kind of a specimen; with those cements containing the lower amounts of alumina and higher silica the magnesia content can be a little higher than this amount. With amounts greater than 10 per cent the early strengths are low, and while they do seem to increase with time at a greater rate than those of normal cements, yet the low early strengths are decidedly against them.

The various test pieces of the high magnesia cements have been carefully examined at all periods at which they were broken for evidence of approaching disintegration. All neat specimens were in good condition at the end of one year excepting those made from burns 32 and 33. In Figs. 7 and 8 are shown the condition of the neat specimens of burn 32 at the end of one year. Particular attention is called to Fig. 8, which shows two of the briquettes placed so as to show the warping produced in the disintegration. The face of the briquettes badly disintegrated and warped to the greatest extent is the face which was next to the glass plate during the storage of the test pieces in the molds in the damp closet. The face showing least warping was the one exposed to the air. This manner of disintegration and warping, relative to the face exposed during the first 24 hours to the air or glass plate, is characteristic. It has also been encountered in the laboratory repeatedly with unsound cements.

FIG. 7.—*Neat briquettes of burn 32 at end of one year*

The faces of the briquettes shown above are those on which the briquettes rested on the glass plate during storage in the damp closet. The faces exposed to the atmosphere during storage in the damp closet are not cracked.

TABLE 8.—Tensile and Compressive Strengths of Neat Test Pieces

[Pounds per square inch.]

Burn No.	Per cent MgO	Method	Tested at end of—						
			24 hours	7 days	4 weeks	13 weeks	26 weeks	1 year	3 years
16	1.77	Tension	275	925	965	951	893	951	799
		Compression	2528	11 343	13 469	14 238	14 849	15 793	16 292
25	3.27	Tension	329	645	623	608	704	693	673
		Compression	2955	5233	6840	7610	9162	9502	8925
26	4.20	Tension	305	609	756	764	688	844	815
		Compression	3102	5818	9851	10 855	11 710	13 507	14 404
27	5.12	Tension	329	657	911	957	1015	928	998
		Compression	3015	7614	10 812	11 821	15 388	13 583	16 412
28	6.49	Tension	292	627	821	827	812	795	920
		Compression	2833	5560	7206	10 363	13 181	11 372	12 090
29	7.41	Tension	258	445	591	774	723	1062	1004
		Compression	2268	4184	6787	9438	10 923	10 321	12 820
30	9.50	Tension	209	300	464	543	647	800	738
		Compression	1318	3078	4794	8112	9089	9730	12 262
31	14.07	Tension	170	196	359	311	377	652	652
		Compression [a]							
32	18.98	Tension	27	30	38	77	73	(b)	(b)
		Compression	292	330	322	564	972	(b)	(b)
33	25.53	Tension	25	24	99	79	124	54	(b)
		Compression	127	311	453	719	2163	949	(b)
34	19.45	Tension	59	165	190	279	258	207	(b)
		Compression	892	1366	2486	5017	4833	7025	(b)
35	13.96	Tension	147	210	142	210	244	277	(b)
		Compression	1414	1695	1910	3471	4696	5128	(b)
36	10.33	Tension	230	242	431	644	625	687	c 778
		Compression	1770	2904	4305	5893	6371	8224	c 6613
37	8.03	Tension	236	381	586	713	712	728	c 859
		Compression	2142	4979	6969	8232	9897	12 308	c 10 481
38	7.80	Tension	345	382	598	647	793	856	933
		Compression	2170	4571	7679	8536	10 183	11 748	7548
39	6.62	Tension	359	495	630	733	719	837	897
		Compression	2746	4554	7582	8378	9504	10 707	7878
40	3.59	Tension	312	642	743	811	850	946	893
		Compression	3058	6717	9178	10 997	11 750	14 022	9610
41	2.01	Tension	354	674	860	736	823	850	865
		Compression	3517	8096	9104	10 760	12 400	15 240	9968

[a] No test pieces made.
[b] Disintegrated.
[c] Specimens are unusually full of crystals, but no enlargement or checking noticed.

Burns 32 to 35, inclusive, during the period between one and three years began to show increasing amounts of disintegration. At the end of this period all of the small specimens of these burns had enlarged to such an extent that they were not tested. It was impossible to place the tension specimens in the testing machine on account of their increased size and the amount of

warping. The compression specimens were also warped and cracked.

An examination of the specimens which have disintegrated shows that the cracks and cavities are filled with crystals of lime hydrate ($Ca(OH)_2$), magnesium hydrate ($Mg(OH)_2$), and sometimes calcium sulphoaluminate ($3CaSO_4 \cdot 3CaO \cdot Al_2O_3 + H_2O$). The first two compounds crystallize very similarly in hexagonal needles or plates, as shown in Fig. 9. The sulphoaluminate crystallizes in very fine needles, which, owing to their slenderness and intermingling, appear in some cavities like a mass of white powder. Such a mass is shown in Fig. 10.

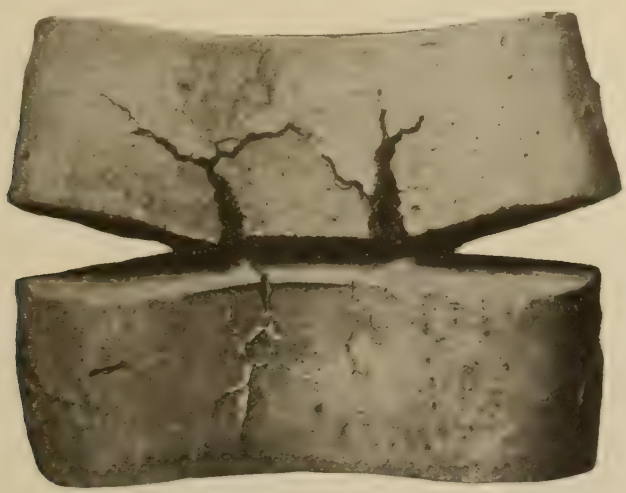

FIG. 8.—*Two of the briquettes of Fig. 7 placed so as to show the warping*

The cracked and most expanded surface was that next to the glass plate while the specimens were in the damp closet

The formation of the sulphoaluminate crystals occurs in larger amounts than has been noted before in this laboratory, but at the same time such pronounced disintegration has not been noted before. The indications, furthermore, would point to the fact that the sulphoaluminate has not produced the cracking, but has leached out into the cracks and voids and crystallized there. Fig. 10 shows this in particular. Here is a crack entirely free of crystals, yet immediately above and spanning it was a cavity well filled with them.

The presence of the magnesium-hydrate crystals can only be explained by the hydration of some of the compounds containing magnesia, which hydration was accompanied by the liberation of magnesia, followed by its hydration and accompanied by a very

FIG. 9.—*A crystal of hydrated lime in a cavity of a neat specimen*

Frequently the cavity is almost completely filled with a network of crystal of this material. Two of such cavities are shown in Technologic Paper 78 of this Bureau. Magnified 16

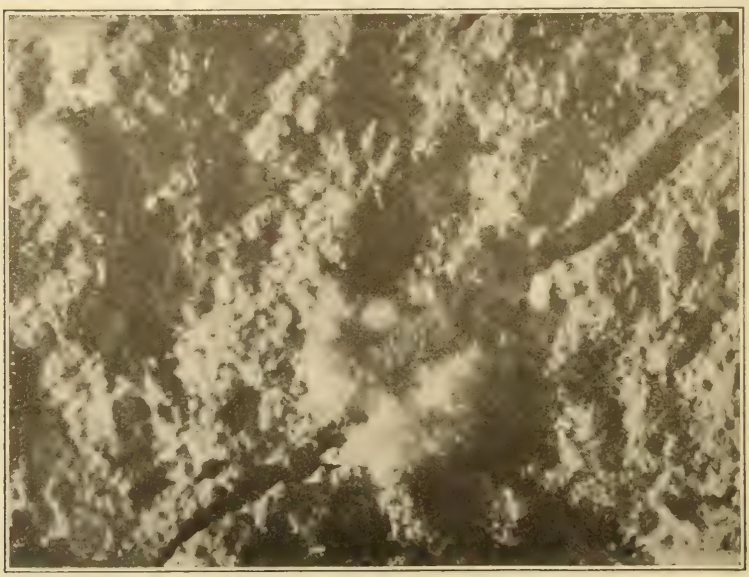

FIG. 10.—*A mass of very fine crystals of tricalcium sulphoaluminate ($3CaSO_4.3CaO.Al_2O_3+H_2O$) spanning a crack in a briquette made from burn 32 which had been stored in water*

The crystals are so fine that they appear as an amorphous mass except directly over the crack where there is a slight indication of their acicular character. Magnified 16

much larger increase in volume than that which accompanied the hydration of lime. The magnesia occurs in these cements, when present in amounts less than 7.5 per cent, combined as a homogeneous compound either with the orthosilicate or the tricalcium aluminate; with greater amounts it is present as monticellite or spinel. So far as the hydration of these compounds is known, it is doubtful if magnesium hydrate would result from the tricalcium aluminate, as when pure it hydrates without splitting off any new compound. A microscopic examination of specimens shows that the spinel has not hydrated. A similar examination shows that the monticellite has hydrated, but the resulting compounds are not known. Recent work in this laboratory has shown that the orthosilicate of lime, in the presence of small amounts of water such as are usually used in making cement test pieces, does split off and allow the formation of calcium hydrate. Hence it would appear that the magnesium hydrate has resulted from the hydration of either the orthosilicate or the monticellite. That its formation would be more destructive than the formation of calcium hydrate is apparent from its relatively greater volume. It should be borne in mind that so far disintegration has been noted only in specimens containing very large amounts of magnesia. These consequently contain considerable amounts of monticellite and also, apparently, have the orthosilicate saturated with magnesia.

(*b*) *Mortar Test Pieces.*—In Table 9 are shown the results from the mortar test pieces. In general these bear out the statements made in regard to this class of cements when tested as neat test pieces. The increase of strength with age of the high magnesia cements in mortars is even more striking than as neat test pieces. This is to be expected, as a mortar usually allows more ready and complete hydration than the neat cement, so that the mortar would show a greater gain. The fact that a cement containing as much as 10.33 per cent magnesia (burn 36) at the end of one year has as a 1:3 mortar a tensile strength of 398 pounds per square inch and a compressive strength of 2802 pounds per square inch is certainly worthy of special mention.

When the three-year results with high magnesia are examined, as well as the three-year results of burn 30 (containing 9.5 per cent of magnesia), the lack of durability of such cements is clearly seen. It should be remembered, however, that in the expected life of a structure three years is a comparatively short time. The need of long-time tests for the other specimens is very clearly shown.

Burn 32 was the first of the cements to disintegrate as a mortar. This was noted at the end of one year. Some of the specimens of burn 33 next showed cracking. At the end of three years the specimens of burns 32 to 35, inclusive, were all enlarged and cracked. As noted above, the enlargement and cracking was least on the sides that were exposed to the atmosphere of the damp closet during the first 24 hours after molding. Fig. 11 shows the

FIG. 11.—*Two-year 1:3 standard sand mortar briquettes of burn 33 (on top) and burn 32 (below)*

This disintegration is characteristic of the very high magnesia cements

condition of some of the cubes of mortar made from burns 32 and 33 at the end of two years.

(*c*) *Concrete Test Pieces.*—The results from the concrete test pieces are shown in Table 10 and Fig. 15. These are the test pieces from which the behavior of high-magnesia cements can best be judged, yet it is readily seen from graphical representation of the results that their behavior was very similar to the small test pieces. It is necessary to increase the magnesia to almost 8 per

cent (the appearance of monticellite in the clinker) before there is any very marked change produced in the physical properties of the cement as a bonding material for making concrete.

TABLE 9.—Tensile and Compressive Strengths of 1:3 Standard Mortars

[Pounds per square inch.]

Burn No.	Per cent MgO	Method	Tested at end of—						
			24 hours	7 days	4 weeks	13 weeks	26 weeks	1 year	3 years
16	1.77	Tension	72	291	322	410	365	414	376
		Compression	398	2030	3516	4522	4199	4666	4329
25	3.27	Tension	156	193	281	363	362	347	203
		Compression	712	1284	1999	2156	3204	3374	2800
26	4.20	Tension	128	291	336	403	445	421	342
		Compression	555	1461	2725	3353	3761	4088	4200
27	5.12	Tension	108	275	445	443	480	459	408
		Compression	515	1326	3042	3379	4754	3896	4363
28	6.49	Tension	99	212	339	381	321	336	242
		Compression	640	1380	2504	3548	3715	3603	3882
29	7.41	Tension	91	149	341	427	430	376	274
		Compression	395	879	1708	2618	3368	3688	3963
30	9.50	Tension	58	110	217	378	367	355	141
		Compression	227	454	1324	1809	2977	2707	2633
31	14.07	Tension	29	52	79	160	186	224	224
		Compression [a]							
32	18.98	Tension	24	26	27	68	102	(b)	(b)
		Compression	117	133	140	288	612	442	(b)
33	25.53	Tension	Soft	Soft	38	87	73	116	(b)
		Compression	27	43	110	148	434	479	(b)
34	19.45	Tension	33	42	41	93	130	145	(b)
		Compression	147	137	545	896	1666	2374	(b)
35	13.96	Tension	69	65	55	134	150	82	(b)
		Compression	494	396	621	873	1628	1018	(b)
36	10.33	Tension	127	115	234	328	440	398	[c] 107
		Compression	318	455	1394	2216	2563	2802	[c] 1154
37	8.03	Tension	90	160	305	448	400	375	[c] 168
		Compression	386	844	2332	3550	3425	3193	[c] 3070
38	7.80	Tension	112	168	252	366	418	319	282
		Compression	489	911	1838	2018	2567	2986	2046
39	6.62	Tension	155	212	345	472	461	500	355
		Compression	653	928	2227	1939	2792	4508	2207
40	3.59	Tension	136	274	368	428	431	407	
		Compression	568	1585	2631	2697	3896	4100	2738
41	2.01	Tension	133	289	406	449	470	422	420
		Compression	673	1857	2696	3320	2758	4383	3315

[a] No test piece made.

[b] Disintegrated.

[c] Specimens are unusually full of crystals, but no enlargement or checking noticed.

As previously noted, the cements with the increasing amounts of magnesia show a very low strength at early periods; but with age the strengths become more nearly uniform, the high-magnesia

cements showing greater gains in strength. As the strengths are compressive strengths it might be argued that this is due to the late hydration of the magnesia compounds and consequent increased denseness of the test pieces, and that this hydration may continue and at very late periods cause disintegration. This may actually be the case, and only tests made after long periods will prove or disprove this statement. At the last period at which the concrete was tested (one and one-half years) there was a very satisfactory gain.

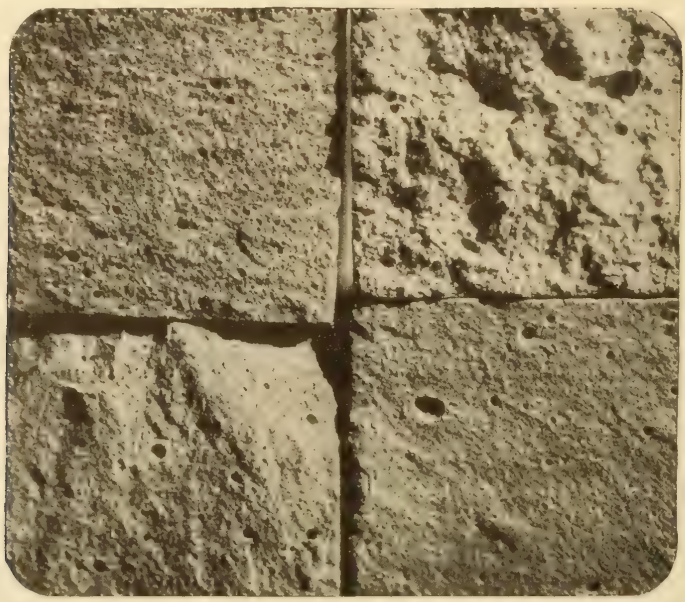

FIG. 12.—*Neat briquettes of the same cement broken: At upper right, 1 day; upper left, 7 days; lower left, 4 weeks; lower right, 1 year*

Note the difference of the fracture of the briquettes at the different periods. Magnified 3

It is well known that the denseness of the test pieces of cements of normal composition increases very markedly as they hydrate. This is seen in Fig. 12, which shows neat briquettes of the same cement broken at the end of 1, 7, and 28 days and 1 year. The continuous decrease in the sandy appearance is so marked as to require no comment, but it can be readily seen that if much further change takes place, especially if the mass hydrates to a different degree in different parts, a very great strain must result. In concrete where the cement is very unevenly distributed very uneven strains might be developed.

TABLE 10.– Compressive Strength of 1:1½:4½ Gravel-Concrete Cubes

[Pounds per square inch.]

Burn No.	Per cent MgO	Stored in—	Tested at end of—			
			4 weeks	13 weeks	26 weeks	1.5 years
18	1.77	Water	3491	4067	4081	6133
		Solution	3388	3829	3435	6245
25	3.27	Water	2910	3625	3765	5084
		Solution	2932	3756	3951	4996
26	4.20	Water	3275	3776	4379	6238
		Solution	3351	4261	4564	6558
27	5.12	Water	3410	4228	4605	6528
		Solution	3427	4194	4318	6276
28	6.49	Water	2489	3493	4185	5843
		Solution	2466	3173	3771	5875
29	7.41	Water	2059	3171	3431	5742
		Solution	1675	2813	3119	4650
30	9.50	Water	1616	2254	2589	4610
		Solution	1305	2343	2563	4068
31	14.07	Water	483	1040	1248	2608
		Solution	533	1342	1488	2989
34	19.45	Damp closet	133	476	787	1589
		Air	63	105	77	100
35	13.96	Water	408	768	1044	2062
		Solution	[a] 308	833	1127	2112
		Air	320	378	512	532
36	10.33	Water	1174	1868	2263	3903
		Solution	1003	1731	1917	3138
		Air	1271	1957	2002	2552
37	8.03	Water	1660	2580	2714	4454
		Solution	2003	2611	2744	3832
		Air	904	1262	1307	1657
38	7.80	Water	1336	2587	3232	4878
		Solution	1794	2624	3192	4697
		Air	1094	1404	1473	1604
39	6.62	Water	2261	3406	3142	4735
		Solution	1972	3330	3381	4186
		Air	1260	1362	1454	1562
40	3.59	Water	2286	2859	3037	4363
		Solution	2364	3032	3440	4522
		Air	1478	1612	1524	1838
41	2.01	Water	2416	2887	3206	4561
		Solution	2045	2729	3180	4348
		Air	1651	1800	1899	1882

[a] Wet when tested.

After the concrete specimens had been in the water or solution for the various alternate periods mentioned above for one year, they were stored continuously in the air of a building the temperature and humidity of which were those usually present in a laboratory. The result of this drying out was a very marked increase in strength at the end of one and one-half years over that noted at the end of a half year. Whether there will be a still greater

increase with time can only be ascertained when the specimens are broken, which will not be before five years. It is rather doubtful if this will be the case, as not only are the strengths abnormally high, but it can be seen from the results on the concrete stored only in air how slowly the hydration proceeded under such conditions.

When the specimens were removed from the solution at the end of one year, they were not different in appearance from those

FIG. 13.—*Pitting on a concrete cube of burn 36 at the end of 2.5 years*

This pitting occurs only over pieces of aggregate very close to the surface. It seems to be due to a more thorough hydration of the cement with a consequent increase in volume. This volume change tends to push the thin layers of cement away from the aggregate

removed from the water, excepting the white appearance due to the deposition of some hydrated magnesia. However, very slowly there appeared a pitting on some of the specimens, and at the end of one and one-half years it was quite marked on the specimens made from burns 36 and 37. At the end of two years it had also appeared on the specimens made from burns 38 and 39, though on the latter it was only seen after very close examination. At the end of two and one-half years the condition of the concrete

cubes of burn 36 is shown in Fig. 13. The character and amount of pitting are clearly shown, though it is not so readily noticeable that at the bottom of each pit is a piece of aggregate. (See Fig. 14.) These pits are not more than ⅛ inch deep. Apparently this has been caused by the solution penetrating through this ⅛-inch layer and, when subjected to the alternate wetting and drying, setting up stresses due to the more complete hydration. These stresses are sufficient to push the material out from the aggregate; but when there was no aggregate immediately present the stresses were distributed over the greater mass. Moreover, a microscopical examination shows complete hydration of both the

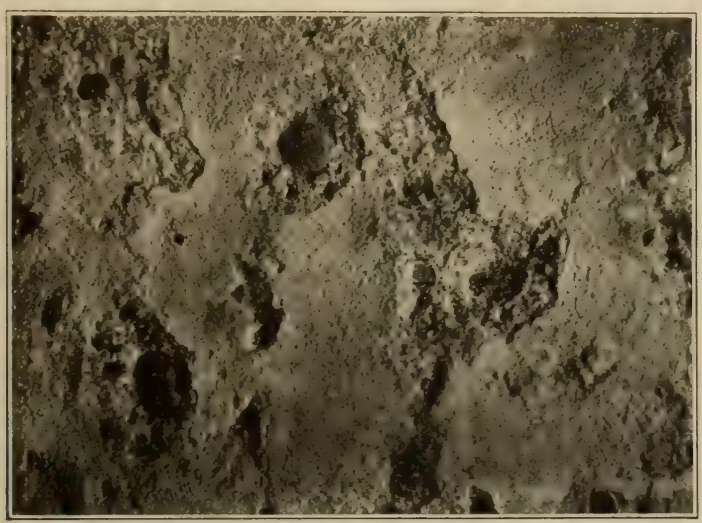

FIG. 14.—*Pitting on a concrete cube of burn 37 at the end of 2.5 years*

At the bottom of each pit is a piece of large aggregate. This is an enlargement of pitting similar to that shown in Fig. 13. Magnified 3

orthosilicate and the monticellite, also a relatively marked absence of crystalline products of hydration (the only pronounced one being calcium carbonate), but a very marked amount of isotropic material. Consequently the blistering has not likely been produced by a mechanical stress set up by the force of crystallization but rather by the uneven strain produced by the complete hydration of this thin layer restrained on one side by the aggregate.

If this explanation is true, then it must also be granted that the salts in the solution have aided this hydration, since the specimens subjected to water do not show the blistering. This is quite likely the case, as in a previous paper from this Bureau

the accelerating influence of a chloride in the solution of cement was shown very clearly quantitatively.[11]

Another feature of this blistering is worthy of note. The cubes were molded in cast-iron molds, which, of course, allowed the

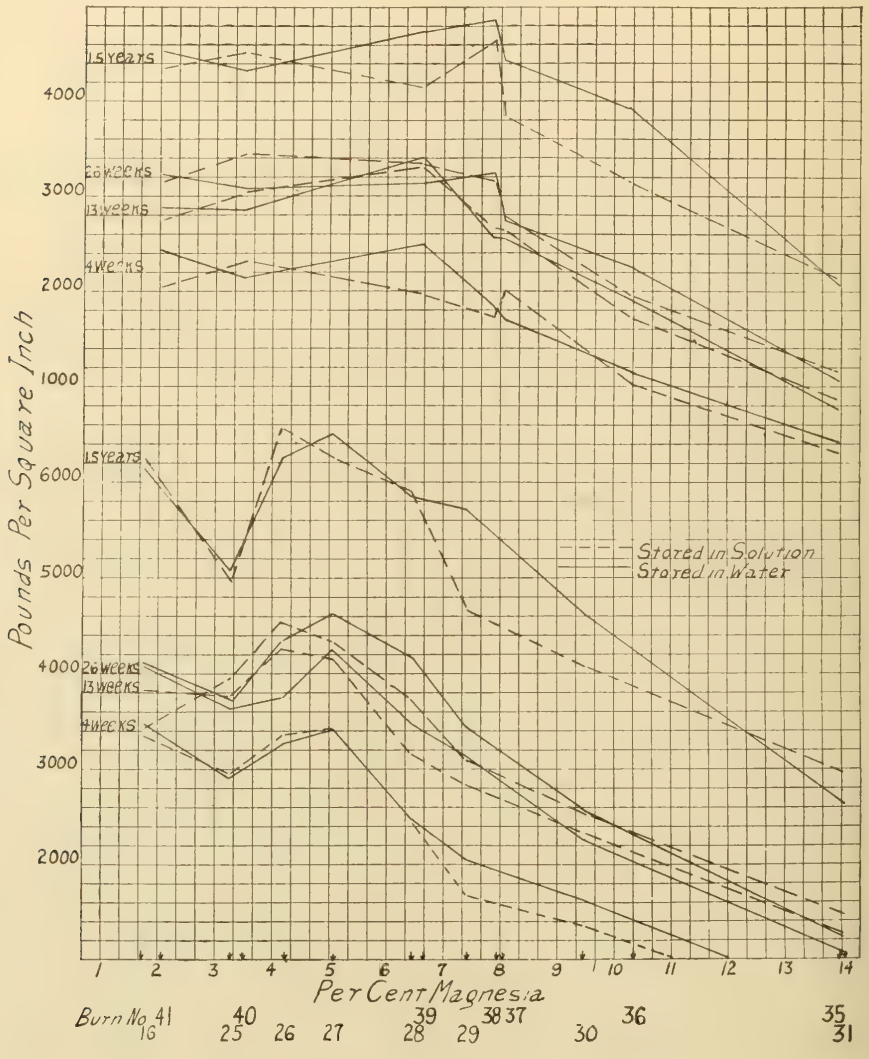

FIG. 15.—*Compressive strength 1:1.5:4.5 concrete*

upper side of the cube to be exposed to atmospheric influence immediately from the time of troweling off the surface. The surface was, therefore, exposed to the action of the carbon dioxide of the atmosphere, while it was still wet, for the first 24 hours

[11] Bates, Phillips, and Wig, "Action of the Salts in Alkali Water and Sea Water on Concrete," Bureau of Standards Technologic Paper No. 12.

after molding and before placing in the solution. This surface does not show any blistering. Apparently the comparatively short period of carbonation was sufficient to bring about a decided protective influence. Attention previously was called to the effect of the atmosphere on the exposed surface of neat briquettes during the first 24 hours after molding, when they are stored in the damp closet. It was shown that this surface warps and disintegrates to a very much less degree than the lower surface, which is protected from the atmosphere by the glass plate upon which it rests.

The concrete cubes of burn 31, which had been stored in water with the alternate dryings, show a number of very fine cracks filled with crystals. The nature and cause of these cracks is a matter of conjecture. They do not appear like disintegration cracks, which are usually very narrow at the center of the face and become larger as they extend toward the edge, but are of uniform thickness throughout their entire length. They appear more like shrinkage cracks, particularly on account of their uniform thickness and their somewhat irregular course on the surface. In view of the fact that these cubes were not placed in the water until the end of a week after making, on account of their very slow hardening, it is quite likely that they are shrinkage cracks, although they were covered with wet burlap during the first week of hardening, and no cracks were noticed when they were first immersed. The cubes of this burn, which had been stored in the solution, do not show these cracks, but this may be on account of the deposition of hydrated magnesia on their surface; the cracks may actually be present.

Another somewhat strange feature of this blistering of the cubes is the fact that it appears upon certain burns while upon other burns of very similar magnesia content it is not noticeable at all. Thus if it were a matter of magnesia alone, why have not the cubes of burns 28, 29, and 30, which have a magnesia content within the same limits as burns 36 to 39, shown the same results? While generally the former burns were of a lower alumina and higher silica content than the latter, this amount appears too small to cause such a difference. But at the same time their higher silica and lower alumina contents give strengths about 25 per cent higher throughout the entire test series. Consequently had the alternate wetting and drying continued, it might have followed that at a later period the cubes of burns 28

to 30 would also have shown the blistered disintegration, they being stronger than the cubes of burns 36 to 39, and consequently requiring a greater force to disrupt the thin film of mortar over the aggregate. In the case of the latter burns the treatment was sufficiently long to bring about the result, but did not extend to a longer period, for this blistering is never more than ⅛ inch deep and seldom that. Furthermore, it had not progressed to such an extent as to actually break the blisters; they were only raised slightly on the surface. The pittings shown in the photograph were produced by breaking the blister by rubbing. The thin exterior film of set neat cement was in almost perfect condition.

V. SUMMARY

1. Portland cement with a magnesia content of about 9.50 per cent may be burned in a rotary kiln without producing a clinker materially different from one containing less than 4 per cent. The clinkering temperature will be reduced somewhat, however. With greater amounts of magnesia present the resulting clinker is very vitreous and dusts more or less slowly, the rapidity and amount of dusting increasing with the magnesia content. High-magnesia clinker is of a light-brown color, in strong contrast to the usual dark, glistening, normal clinker. The resulting ground cement is of a light-brown color, which makes a concrete decidedly different in color from concrete made from normal cement.

2. No new constituents are present in the high magnesia cements until the magnesia has reached about 8 per cent. A very small amount of the mineral monticellite ($CaO.MgO.SiO_2$) is then noted. The amount of this constituent increases rather rapidly with the increase of the amount of magnesia. Further, when the latter has reached about 10 per cent, the mineral spinel ($MgO.Al_2O_3$) is noted; this also increases in amount as the magnesia increases. There was about 23 per cent of monticellite present in the clinker made from dolomite only (25.5 per cent MgO). The amount of spinel was not determined in this case, but it was not more than a minor constituent.

3. With the largely increased amounts of magnesia the amount of orthocilicate of lime was very decidedly decreased. The amount of tricalcium silicate was not affected materially. As the amount of spinel was very small in any case, the amounts of tricalcium aluminate were only slightly decreased in the case of the higher magnesia clinker.

4. The structure of the very high-magnesia clinkers was decidedly different from those of normal composition. The former were much more crystalline in character, the crystals having developed to a comparatively large size and with well-defined outline. In normal clinker the crystals are not only small but usually lack outline, being fused into and surrounded by the invariably poorly crystallized orthosilicate.

5. When the magnesia content did not exceed 9.5 per cent, there was no marked change noted in the time of set, though there was apparently a slight tendency toward slower final set. When the magnesia exceeded this amount, the initial set became quite rapid, accompanied by a marked evolution of heat. In some cases this produced a drying out, which caused the appearance of a quick, false, final set. In other cases the evolution of heat was not so marked, and there resulted a slow final set. This quick initial set could be predicted from the changes noted, by the microscopic examination, in the structure and the character of the constituents of the clinker. In this class of cements the constituents are well defined and not surrounded so uniformly by the slow-hardening orthosilicate. Furthermore, the amount of this latter constituent is materially reduced in the high-magnesia cements, while the quickly setting aluminate and tricalcium silicate are but slightly changed in amount.

6. With the exception of two of the very high-magnesia cements the other high magnesia cement pats showed these cements were sound either when stored in water for 28 days or in air for 28 days or subjected to boiling water or steam at the end of 24 hours. These two unsound cements developed a very slow final set, and when subjected to the boiling and steaming tests had not attained their final set; consequently, after the test they were soft and somewhat enlarged. (Burns 25 and 26, of low magnesia content, were also unsound, due to inability to secure sufficient gas for proper burning.)

7. The strengths developed, either by the neat cement or 1:3 sand mortar or 1:1½:4½ gravel concrete, show that cements containing as much as 7.5 per cent of magnesia are satisfactory. It would be impossible to predict from the strength tests at the end of one and one-half years which were the cements containing low magnesia or magnesia up to 7.5 per cent. With higher amounts the strengths developed decreased with increased magnesia, but even with the high-magnesia cements there is a notable increase of strength with age.

8. The strength of the concretes subjected to the action of the solution of salts was not materially different from that of those subjected to the action of water. While some of the specimens did show a slight disintegration, it was not sufficient to affect their strength at the last period at which they were tested, and, furthermore, it appeared in the case of concrete made from cements of moderate magnesia content and was not noted in those of high magnesia content.

9. The high-magnesia cements contain a large amount of "insoluble residue."[12] This residue is the monticellite and spinel, both of which are very largely insoluble in dilute acids.

10. Measurements to determine changes in the volume of the concrete with the progress of hydration, show in some cases a slightly greater change produced by the high-magnesia cements than by the low-magnesia ones.

11. Strength specimens to be tested at still later periods than those reported in this paper are on hand. It may be that at very late periods some of the conclusions which appear justified from the present results may require revision.

Attention should again be called to the fact that the work presented in this paper was not undertaken to show the advisability of allowing a greater magnesia content in cement, but only to determine how greater amounts of magnesia affect the constitution and properties of cement of normal composition.

Acknowledgments are due to A. A. Klein for the petrographic examinations and to E. R. Gates for superintending the molding and breaking of all test pieces.

WASHINGTON, MAY 1, 1917.

[12] Bureau of Standards Circular No. 33; United States Government Specifications for Portland Cement.

DEPARTMENT OF COMMERCE

TECHNOLOGIC PAPERS

OF THE

BUREAU OF STANDARDS

S. W. STRATTON, DIRECTOR

No. 103

TYPICAL CASES OF THE DETERIORATION OF MUNTZ METAL (60:40 BRASS) BY SELECTIVE CORROSION

BY

HENRY S. RAWDON, Associate Physicist

Bureau of Standards

ISSUED DECEMBER 15, 1917

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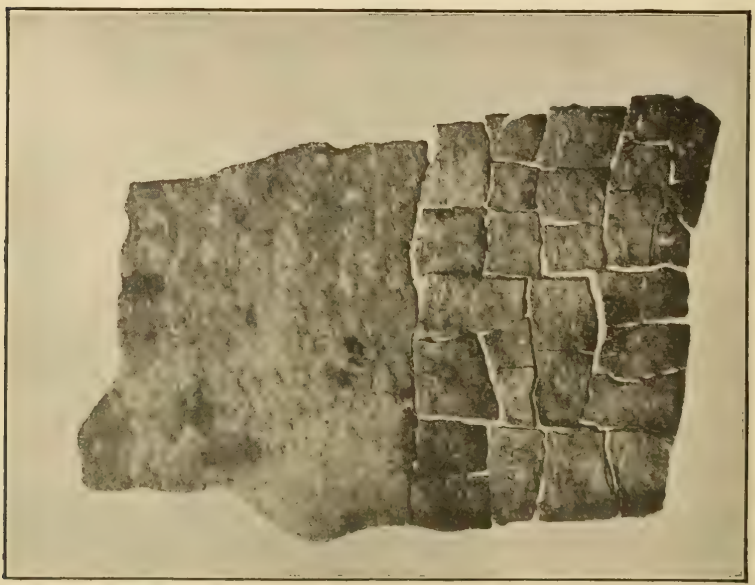

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FIG. 1.—*Types of corroded Muntz metal*

(*a*) Surface of a badly corroded Muntz metal bolt.

(*b*) Cross and longitudinal sections of the corroded portion of bolt *a*, unetched (×2). The outer or attacked portion is copper-red; the center has the yellow color of uncorroded brass.

(*c*) Boat sheathing after dezincification (×1). The portion at the right was broken into the fragments shown by the fingers alone.

TYPICAL CASES OF THE DETERIORATION OF MUNTZ METAL (60:40 BRASS) BY SELECTIVE CORROSION

By Henry S. Rawdon

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I. INTRODUCTION

Brass of the type 60 per cent copper and 40 per cent zinc, known under various trade names, primarily, however, as Muntz metal, has a variety of industrial uses, such as sheathing for boat bottoms; tubes for condensers; wrought forms, as bolts and rods; irregular extruded shapes, such as handrails for stairway balustrades, etc. One very common type of deterioration of metal of this composition, particularly when exposed to some electrolyte (e. g., sea water), is selective corrosion or "dezincification," the term "selective corrosion" being used to signify a corrosive attack of certain of the microstructural constituents of the alloy rather than a general uniform action upon the metal as a whole. Though this type of deterioration of brass has been known for years and numerous references on this subject have appeared in the technical

literature [1] the description of the various forms in which it may occur and of the changes produced in the metal by which it may be detected are very meager. The numerous samples illustrative of this type of metal failure submitted to this Bureau for examination, together with the inquiries received on this subject, suggested the utility of a description of typical cases of metal affected by this type of nonferrous corrosion as an aid in the detection and identification of similar cases of this type of deterioration of metals. A study of the various forms in which this type of corrosion may occur, together with the resulting structural changes within the metal, also aids in defining the conditions which are most favorable for such deterioration to occur.

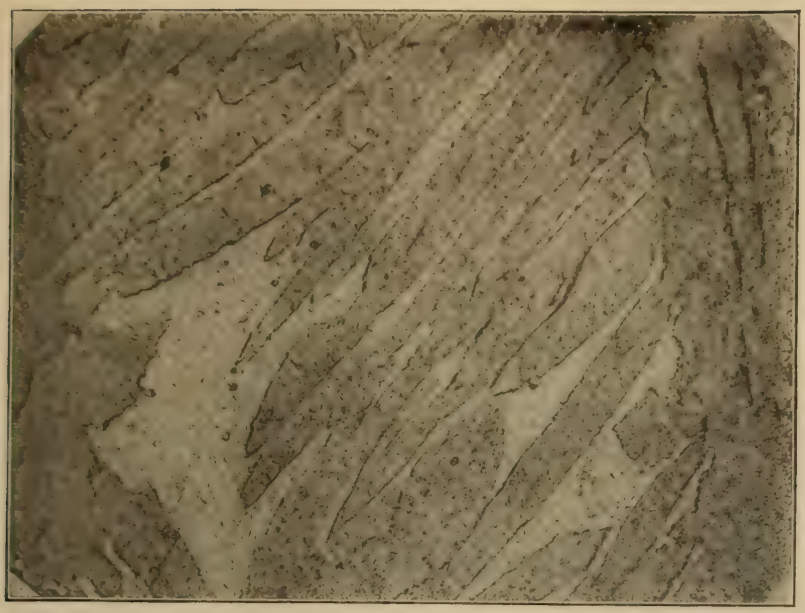
II. CHARACTERISTIC APPEARANCE OF TYPICAL CASES

In general, by the attack, or process of dezincification, the clear yellow Muntz metal having an ultimate strength in tension of approximately 40 000 to 60 000 pounds per square inch, depending on the physical condition of the metal, is converted into a reddish-colored mass resembling poor copper, often so weak that it may be easily broken by the fingers alone or chipped and cut with a knife, though it still retains the initial shape and size. The red color of the attacked metal is intensified by rubbing the part with a cotton swab soaked in dilute ammonium hydroxide and then rinsing with water. The surface is freed from its film of oxide and the unattacked portions assume the original yellow color, the corroded spots become a brownish-red. Below are described five typical cases selected from material of this kind which was submitted to this Bureau for examination.

1. WROUGHT BOLTS

The Muntz-metal bolt illustrated in Figs. 1 and 2 was taken from the keel of a seagoing lifeboat after six years' service. The sample shown is illustrative of the condition of all the bolts used in this particular case to attach the keel to the keelson. To the casual observer the broken bolt appears to consist of a brass center with a heavy deposit of porous copper covering it. The location of that part of the bolt which was most severely attacked and its relation to the position within the keelson is of interest and is suggestive of one of the possible contributing causes to this type of corrosion. This is shown in Fig. 3.

[1] See, for instance, Second and Third Reports of the Corrosion Committee of the Institute of Metals, Jour. Inst. of Metals, 1913, X, and 1916, XV, respectively; J. O. Arnold, Engineer, 85, p. 363, 1898; and Milton and Larke, Proc. Inst. Civ. Engr., 154, p. 138, 1903.



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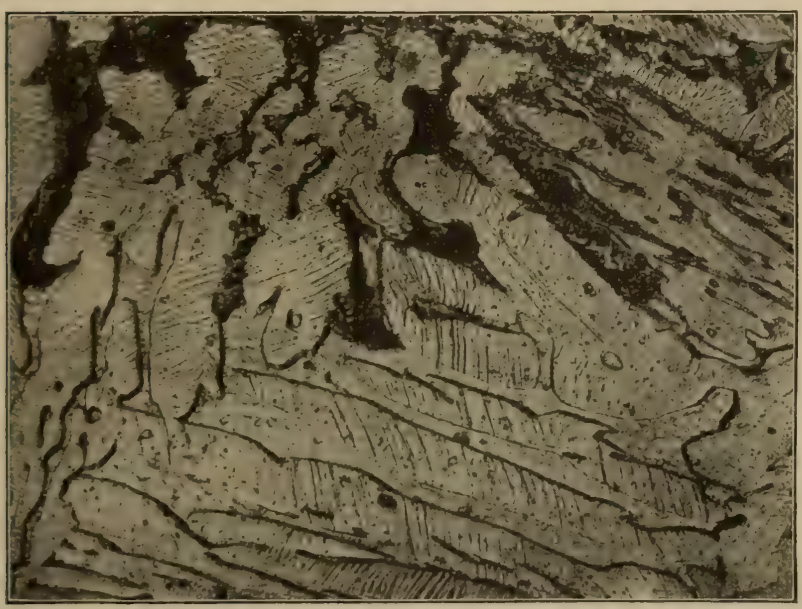

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FIG. 2.—*Microstructural changes induced in Muntz metal by dezincification*

(*a*) Unattacked Muntz metal (Fig. 1, *b*). The light-colored matrix is the zinc-rich or β constituent, in which are embedded the finger-like crystals of the α or constituent richer in copper. (×500.)

(*b*) Corroded Muntz metal. At the edge of the corroded portion (Fig. 1, *b*) the β constituent has been converted into a porous mass of copper (black in the figure) which still retains its former shape. (×500.)

Etching in both cases, ammonium hydroxide and hydrogen peroxide.

It will be noted that the portion of the bolt which was most deeply corroded is that part which was subject to the greatest service stresses (transverse bending). Although apparently this material gave six years' service, it should be borne in mind in

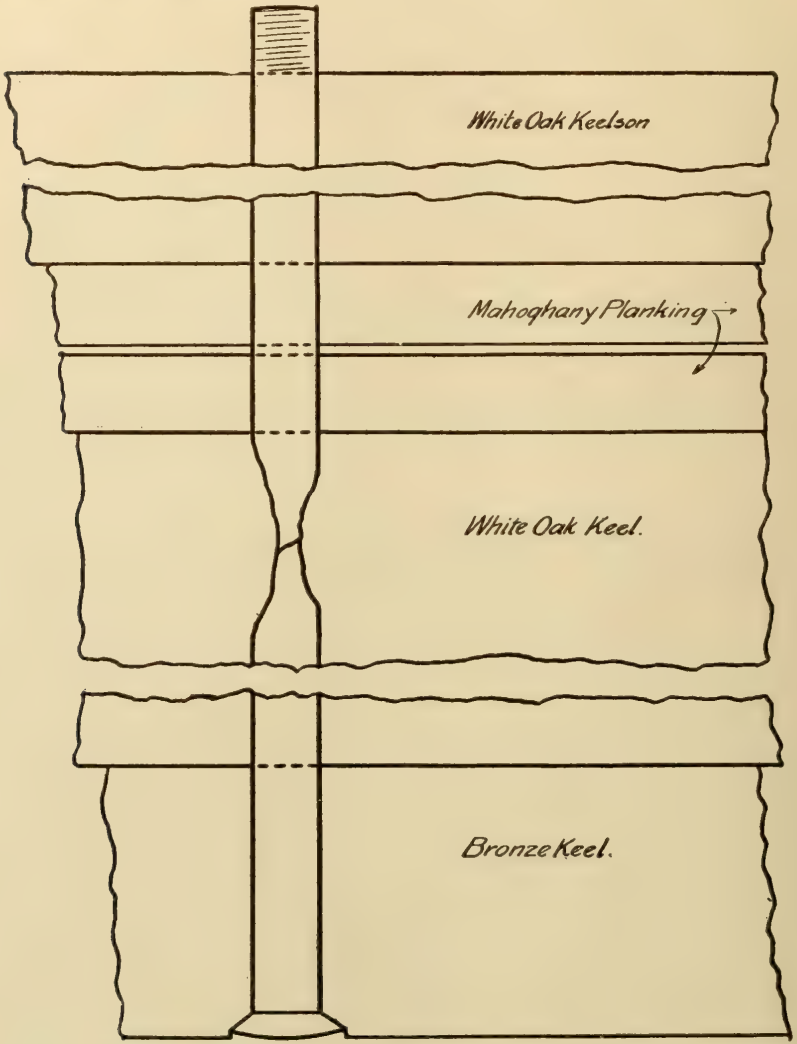
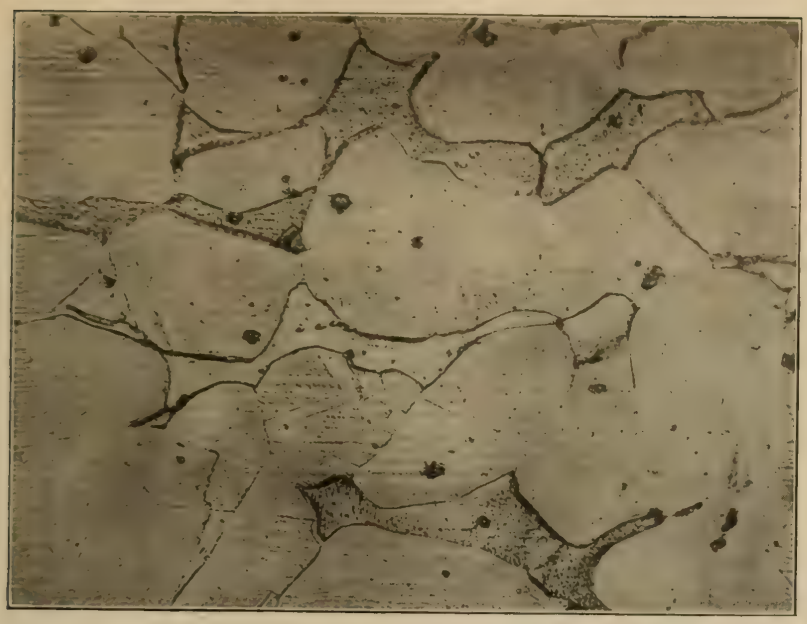


FIG. 3.—*Arrangement of the Muntz metal bolts (type 1) in the keel of the boat*

The part which was most severely corroded corresponds to the portion most highly stressed (i. e., transversely) in service.

comparing this case with the others described that the bolts were not constantly bathed in sea water for this period and that the periods of attack were intermittent, as illustrated by the concentric lines in Fig. 1*b*.



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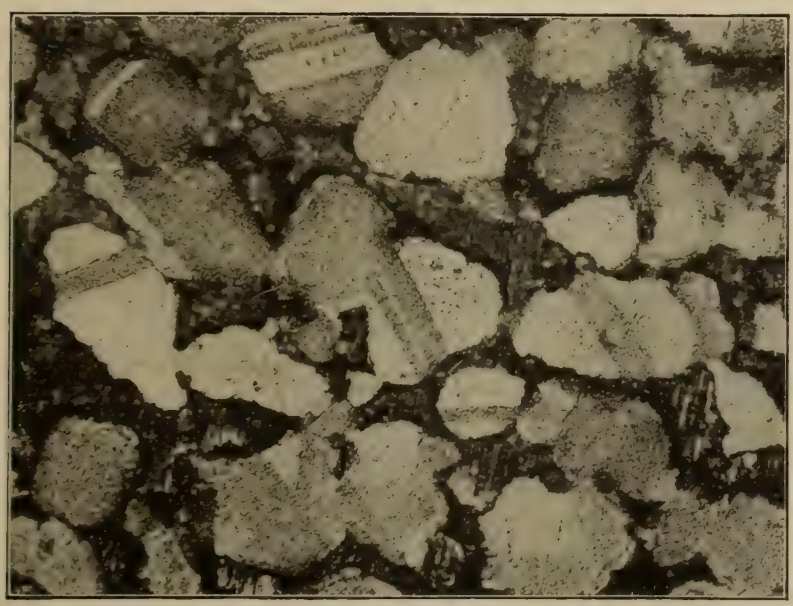

b

FIG. 4.—*Corroded Muntz metal sheathing*

(*a*) Before attack; the light-colored β matrix fills in between the α crystals.
(*b*) After 7 years' exposure to sea water (see Fig. 1, *c*) the β constituent has been entirely changed; the α, apparently not at all. The numerous twinned crystals in the α is indicative that the metal was annealed before use.
Magnification in both cases (×500.) Etching, ammonium hydroxide, and hydrogen peroxide.

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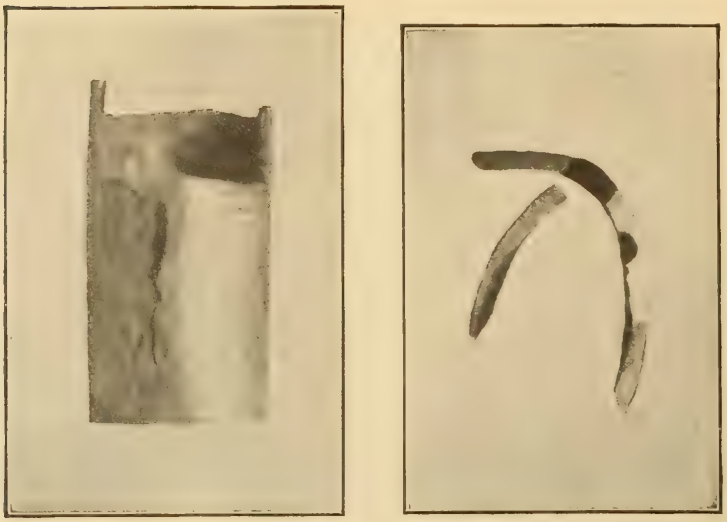

a *b*

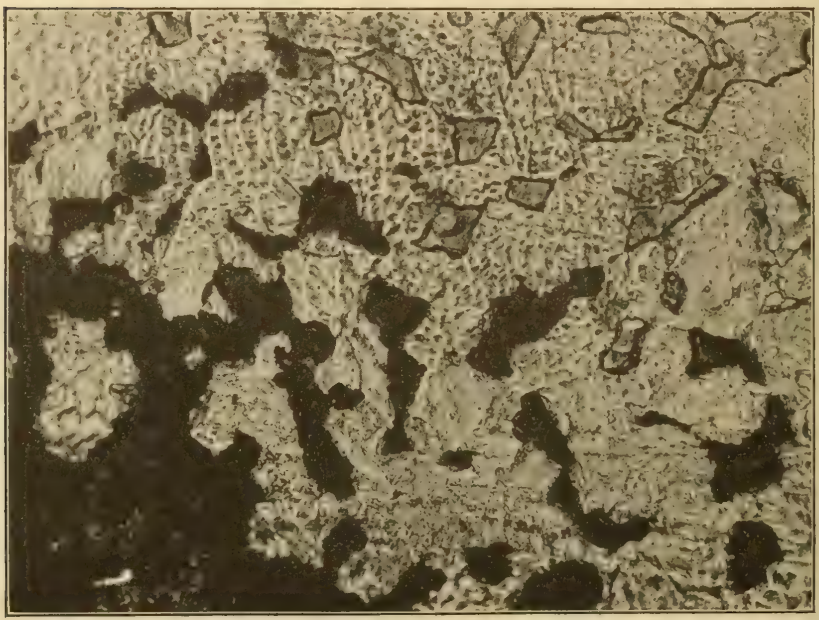

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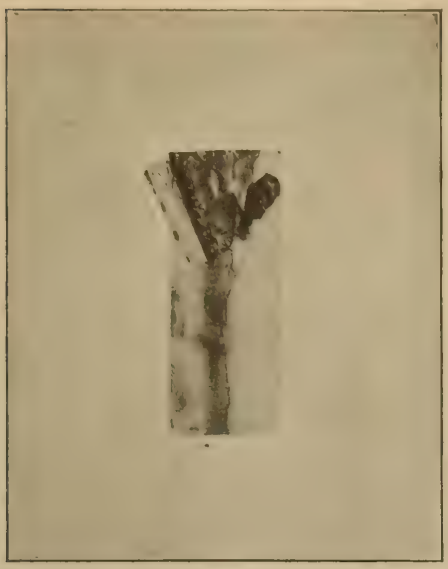
FIG. 5.—*Corroded Muntz metal condenser tube*

(*a*) Appearance of the corroded tube. The darker portions are copper-red and very brittle. The metal here is easily cut with a knife. (×1.)

(*b*) Cross sections of parts of *a*. In the dark portions the metal has been corroded throughout the entire cross section. (×2.) Etching, concentrated ammonium hydroxide, and hydrogen peroxide.

(*c*) Microstructure of the metal of *a*. Both α and β constituents are attacked; a definite zone in which the β, only, is attacked separates the unchanged metal from the completely corroded portion. The α shows little or no evidence of annealing. (×500.) Etching, concentrated ammonium hydroxide and hydrogen peroxide.



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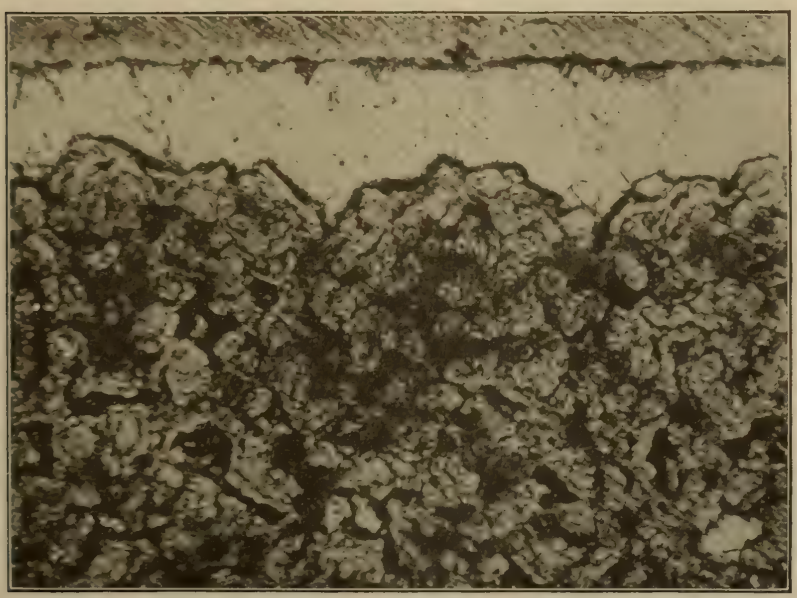

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FIG. 6.—*Corroded Muntz metal condenser tube*

(*a*) Appearance of the corroded tube. No evidence of corrosion shows on the exterior, a thin unattacked layer of α completely masks the corroded portion below. This outer layer is easily stripped off as shown.

(*b*) Material of *a* (×250). Etching, concentrated ammonium hydroxide, and ammonium persulphate. The outer thin layer of unattacked α is due to some zinc being volatilized from the surface during some stage in the manufacturing process.

2. SHEATHING

The sheathing shown in Figs. 1 and 4 was used for seven years upon an anchored lightship. The attack was local, certain isolated sheets only over the bottom of the boat were in the condition illustrated; others, though much thinner than when rolled, apparently were in the same structural condition as when placed in position.

3. CONDENSER TUBES

The condenser tubes are illustrative of a case in which this type of corrosion is very prevalent. Both the samples shown (Figs. 5 and 6) are from condensers using salt water. Type 3*b* (Table 1) is of particular interest in that it illustrates how this type of attack may be entirely hidden from view.

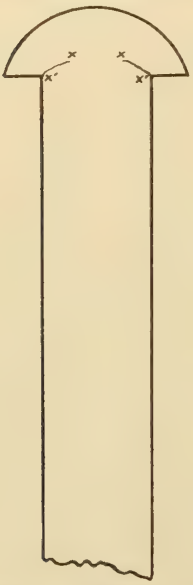


FIG. 7.—*Diagram of the fracture of Muntz metal bolthead (type 4, Table 1)*

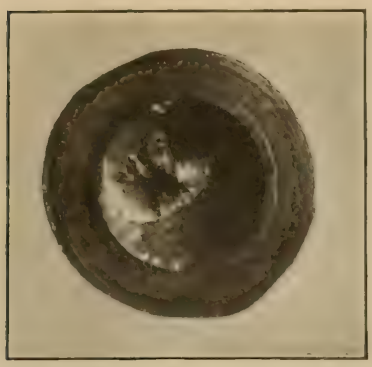
The outer layer of the tube shows no evidence of attack, and subsequent examination showed that this outer portion contained but one constituent—the α. During some phase of the manufacturing process, the tube was evidently heated strongly enough so that a sufficient amount of zinc was volatilized from the surface as to leave the composition here such that only the α constituent was present.

The corrosive attack which proceeded outward from the inner surface, which was in contact with the sea water, proceeded up to this outer α layer; the layer itself, however, remained unattacked and the tube appeared to be unchanged. This outer α layer can be easily stripped off from the corroded metal beneath, as shown in Fig. 6.

4. CORROSION OF PARTS WHILE UNDER STRESS

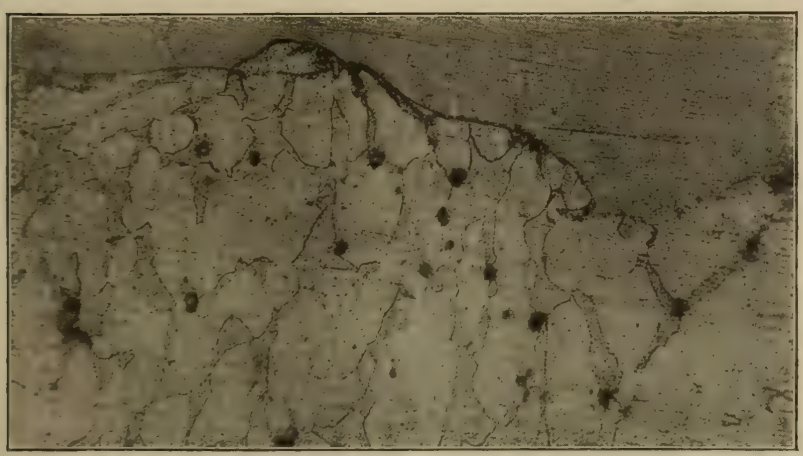
Type 4 (Table 1) is particularly instructive in suggesting service conditions which may aid in this type of corrosion. Fig. 8 shows the face of the bolthead which was fractured as shown in Fig. 7. The head detached itself apparently spontaneously in service, suggesting in this respect the "season cracking" of brass. Dezincification of the surface metal in the outer marginal area, $x-x'$, occurred and penetrated to a depth of from 0.05 to 0.36 mm; the central area shows no corrosive attack, the fracture here having the appearance of a direct tension break. The most severe attack was near the apex of the right angle beneath the head. The easiest and most logical explanation is that the failure in this case is one of corrosion under stress.[2] The starting point perhaps may have

[2] For description of such cases of corrosion of brass under stress, see E. Jonson, Proc. Am. Soc. Test Mtls. p. 101, 1915; and P. D. Merica, B. S. Tech. Paper No. 83.



a

b



c

FIG. 8.—*Muntz metal bolt corroded while under tensional stress*

(*a*) Face of the fractured head. The central portion *x-x*, has the appearance of a simple tension break; the marginal area *x-x'* which resembles a "detailed" fracture shows dezincification of the β. (×1.)
(*b*) Edge of the fracture of area *x–x*. This portion shows no change in structure. ×250.
(*c*) Edge of the fracture of area *x–x'*. The β constituent at the extreme edge has been dezincified. ×250.
Etching in both cases, ammonium hydroxide and ammonium persulphate.

been an initial flaw in the material, such as a forging crack. The β constituent appears to have become dezincified in the region of greatest stress—that is, in the sharp right angle—and to have preceded and accompanied the gradual or detail fracturing of this portion of the break until the central portion became so small that it broke in direct tension under the stress of the applied load the bolt carried.

Below are summarized the different types described, the service to which the material has been subjected, the macroscopic characteristics, the changes in the microstructure, as well as the chemical composition where available.

TABLE 1

Summary of Materials Described

Material	Service	Macroscopic appearance of corroded material	Microscopic structure	Chemical composition (in per cent)
1. Bolt of Muntz metal [a]	Attachment of bronze keel to oak keelson of seagoing lifeboat. Six years' intermittent service. All the bolts showed the same appearance.	In cross section it shows a yellow center and red outer layer and has the superficial appearance of a brass rod heavily copper coated; the coating is very brittle.	Both α and β constituents are attacked in the greater portion of the corroded part; on the inner margin only the β or zinc-rich matrix is replaced by "copper."	Initial: Cu, 59.7; Pb, 0.19; Sn, not detected; Zn (dif.), 40.11. Attacked portion: Cu, 93.4; Pb, 0.06; Sn, trace; Zn, and basic chlorides, etc. (dif.), 6.5.
2. Muntz metal sheathing. [b]	Used for seven years as sheathing upon an anchored lightship in latitude of New York (approx.).	Isolated sheets only were attacked, not the whole bottom. Sheets are somewhat thinner at first and are covered with basic deposits. Metal is brown and spongy and very brittle.	β constituent alone has been replaced throughout by porous "copper"; the α is unattacked.	Initial (according to specifications): Cu, 59 to 62; Zn, 41 to 38; Pb (max.), 0.60. Final: Cu, 75.79; Pb, 0.68; Sn, 0.36; Zn, 20.01; Fe, 0.16; S, 0.07; Cl, trace.
3*a*. Muntz metal tube. [c]	In a condenser using sea water six months.	Tube has a mottled appearance of yellow and red, red being most abundant on inner side. Tube is cracked along one side where the red had penetrated to the exterior.	Both α and β are attacked in completely corroded parts. In outer margins of corrosion spots only β is attacked.	Initial: Cu, 61.7; Pb, 0.2; Fe, trace; Sn, not detected; Zn (dif.), 38.1.
3*b*. Muntz metal tube. [b]	In a condenser using sea water; term of service unknown.	The exterior of the tube is bright yellow, and shows no corrosion. This yellow layer which is very thin can be striped off, and reveals the porous red metal beneath.	Both α and β constituents have been attacked on the side of the tube showing greatest corrosion. A clear yellow unattacked layer on the exterior consists of the α constituent only. The extent of the attack has been limited by this.	
4. Muntz metal bolthead. [e]	Term of service, two years. The bolt which was in tension was exposed to sea water. The head dropped off of its own accord.	The center of the fractured face has the appearance of a tension break; the outer margin, that of a detailed fracture.	The constituent has been attacked in the outer marginal area of the face of the fracture to an average depth of 0.05 to 0.36 mm.; neither α nor β have been changed in the central area.	Copper, 60.95; lead, 0.13; tin, 0.59; Fe, 0.00; Zn(dif.), 38.33.

[a] See Figs 1 and 2 *a* and *b*.
[b] See Figs. 1*c* and 4 *a* and *b*.
[c] See Fig. 5 *a*, *b*, and *c*.
[d] See Fig. 6 *a* and *b*.
[e] See Fig. 7 and 8 *a*, *b*, and *c*.

III. MICROSTRUCTURAL FEATURES

1. UNCHANGED MUNTZ METAL

In order to understand clearly the method by which such pronounced changes in structure, composition, and properties are brought about, a knowledge of the microstructure of the alloy is

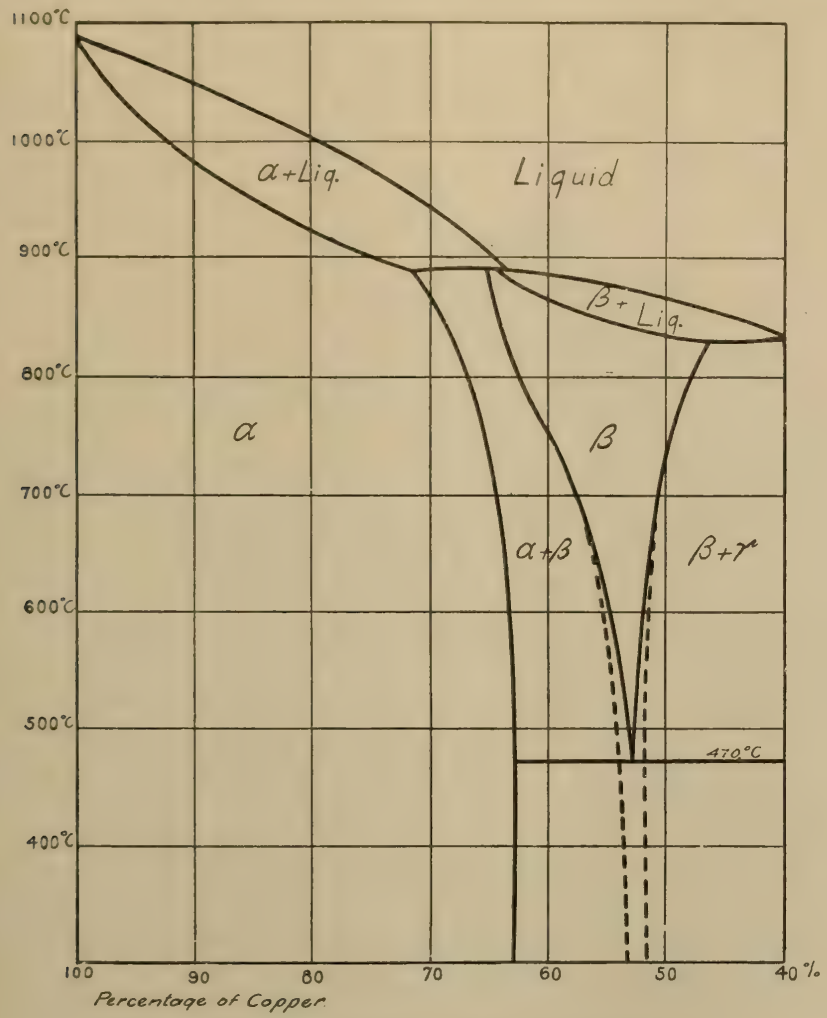


FIG. 9.—*Structural diagram of the copper-zinc alloys*

essential. The metal has a duplex structure, as is shown by Fig. 2*a*. As an example, consider the alloy of 60 per cent copper and 40 per cent zinc, the crystals or "grains" which, when heated sufficiently, are homogeneous throughout, on cooling break up into a complex of two constituents, as shown by the structural diagram (Fig. 9). This is brought about by a crystallization within and

throughout the previously homogeneous grain by which the crystallites or "fingers" of the new constituent form out of the substance of the mother matrix and remain embedded in it. The ground mass (Fig. 2*a*) is the zinc rich or β [3] constituent; the darker fingers embedded in this matrix, the α constituent, which in its saturated condition consists of very nearly 64 per cent copper and 36 per cent zinc. The percentage composition of the zinc-rich or β matrix will vary with the ultimate composition of the alloy in question, but it is always considerably richer in zinc than is the α phase.

In passing, it should be remarked that the color of the two constituents may be varied considerably by the etching medium used. However, with slight etching by means of alkaline reagents, the β always appears yellow at first; deeper etching or other conditions—e. g., slight oxidation of the surface—may cause it to appear darker than the α. In no case, however, was the β found to appear red as is stated by some observers [4] of this alloy.

2. MICROSTRUCTURE AFTER DETERIORATION

There is to be observed a very sharp line of demarcation between the attacked and unattacked portions. The change in composition and properties is not a gradual one, but is very abrupt and complete. After corrosion the attacked portion of the metal consists of a porous mass, apparently of copper, still showing indistinctly its initial structural arrangement. Often well-defined laminations parallel to the corroded surface are seen, corresponding undoubtedly to the intermittent periods of service to which the metal was put (Fig. 1*b*). The interstices of the porous "copper" are filled with basic chloride deposits—the products of corrosion. These are very abundant in the inner layer adjacent to the unattacked metal and under the microscope appear blue-gray in contrast to the red of the copper.

At the boundary surface between the changed and the unchanged portions is plainly seen the method of attack. Figs. 2*b* and 5*c* show this. The β or zinc-rich matrix is the constituent which is first acted upon, and appears to be replaced by one higher in copper; in reality it is not a "replacement." The preferential attack of the β phase is to be attributed to its higher zinc content, which renders it more electropositive than is the α constitu-

[3] This assumption disregards the question whether this constituent is β', a polymorphic modification, or an intimate mixture of two other phases, α and γ. (See Jour. Inst. Metals, 1912, VII, p. 70, and 1912, VIII, p. 51.)

[4] Shepherd, Jour. Phys. Chem., 1904, VIII, p. 421; and Gulliver, Metallic Alloys, p. 269.

ent which is richer in copper. When an electrolyte is present and electrolysis occurs either by means of the application of an external emf, by contact with some metal which is less electropositive than either constituent of the alloy or by reason of the electrochemical difference between the α and β phases, the β is always attacked first; its zinc largely passes into the solution leaving behind the porous copper masses occupying the spaces initially filled with the β matrix. This type of corrosion may be then regarded as an electrolytic "leaching out" of the zinc. The α constituent is later often attacked, so that the copper content of the whole mass may be raised as high as is indicated in Table 1.

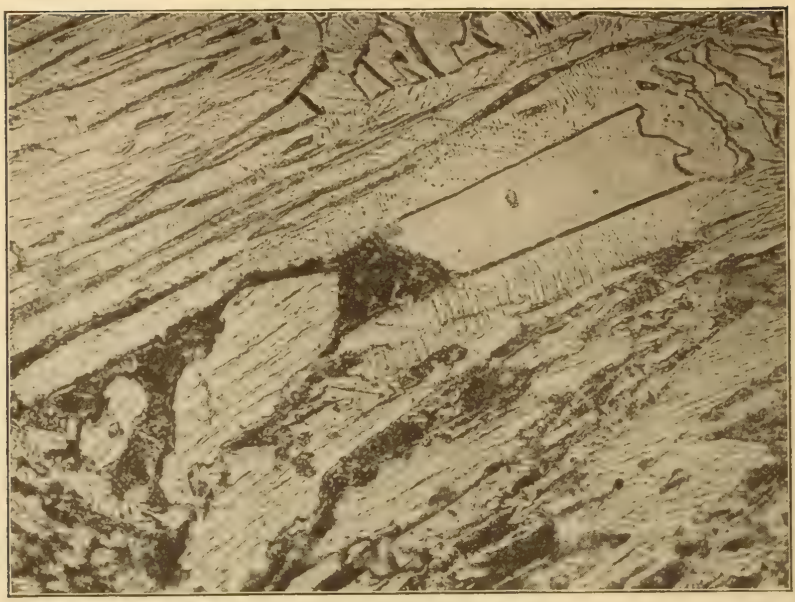
A definite, though narrow, intermediate zone in which the β is completely attacked always precedes and separates the layer in which the attack upon the α begins from the unchanged material. It is to be expected from theoretical considerations that the rate of corrosion of pure β or of pure α brass is much less than that of the α–β metal. Desch and Whyte [5] have shown that such is the case.

The extent to which the α constituent is affected determines largely the properties of the corroded metal. In the case of the Muntz-metal sheathing described, the α remained unattacked even after seven years of exposure to sea water. The sheet, when cleaned, still retains much of its yellow color and is not nearly so brittle as some of the other samples. The metal after the attack consists essentially of a skeleton of α, the pores and interstices of which are filled by the pulverulent copper which resulted from the corroded β crystals. In the bolts described (type 1), the attack, though similar, is very different in regard to the rate at which the corrosion of the α phase follows that of the β. The attack of this constituent follows almost immediately that of the β grains, the intermediate layer in which only the β is attacked averaging only 0.25 mm in depth. The same is true of the condenser tube (type 3*a*); the deterioration of the α follows very quickly that of the β.

3. BEHAVIOR OF α BRASS UNDER SIMILAR CONDITIONS

The behavior of α brass—that is, brass in which the copper is high enough so that the β constituent is entirely absent—when placed in comparable conditions is of interest. Fig. 10*b* illustrates how this behavior differs from that of metal containing both phases. The material here shown is from brass bolts which

[5] Jour. Inst. of Metals, 1914, XI, p. 235; ibid., 1915, XIII, p. 80.



a

b

FIG. 10.—*Method of dezincification*

(*a*) Method of attack within the β crystals. The attack here as shown by the large central β grain is not a gradual one but abrupt and complete. (×500.) Etching, ammonium hydroxide and hydrogen peroxide.

(*b*) Corrosive attack of α brass. The material (bolts) was used in a "water" rheostat. The attack induced by the external emf is very complete and shows a slightly greater rate of attack at the crystal boundaries. (×500.) Etching, ammonium hydroxide and hydrogen peroxide.

were used in the construction of a "water rheostat." The macroscopic appearance is very similar to that of attacked Muntz metal. Fig. 10*b* shows, however, that the method of attack is very different. The normal (i. e., unchanged) metal consists of the polyhedral crystals of the α solution of zinc in copper with the numerous twins characteristic of annealing after strain. In any section the line separating the corroded portion from the unchanged center is very smooth and even. A few sharp bends in this line are to be noticed. These peaks are found to correspond to crystal boundaries, thus indicating a slightly faster rate of attack on the crystal surfaces, which is to be expected from theoretical considerations. Aside from these variations the whole "line of attack" is very even and shows no such preferential action as when both constituents are present.

4. PROGRESS OF ATTACK WITHIN THE β CRYSTALS

In Fig. 10*a* is shown the method of attack within the individual β crystals of Muntz metal. The advance within each β crystal is very uniform and similar to that within any crystal of α when but one phase is present. The line separating the unchanged β from the porous "copper" which results from the attack is very distinct; the change is not a gradual one even here, but is abrupt and complete.

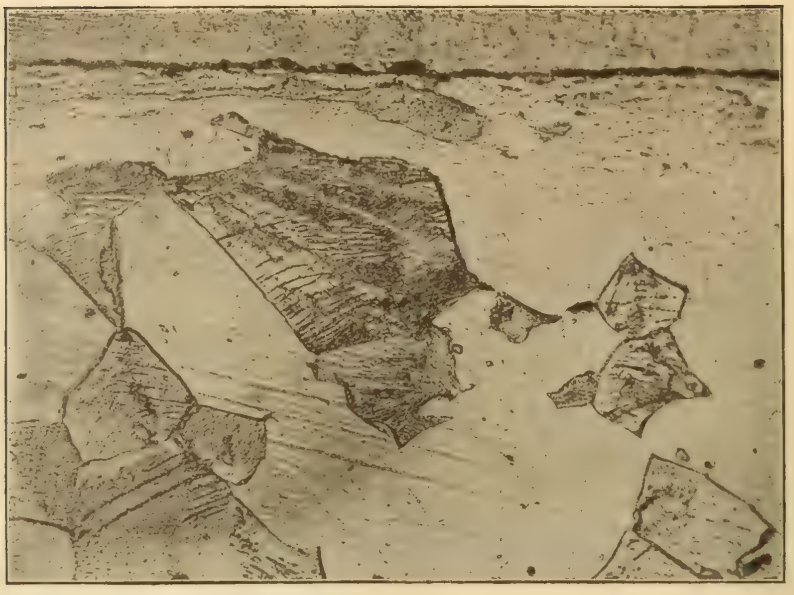
The above is true, however, of β which is in an annealed state. Metal which was quenched (the sample used was quenched in water from approximately 675° C) shows an attack of the β very different from that ordinarily observed. The β crystals in this case are attacked most readily along certain planes, often along two sets of intersecting planes within the same crystal (Fig. 11 *a* and *b*). The attack then proceeds from these planes of attack until the whole crystal has been converted into the same condition as occurs more directly in the annealed material.

IV. CONDITIONS INFLUENCING DEZINCIFICATION

1. STRUCTURAL COMPOSITION

Although α brass is subject to dezincification, the attack is not nearly so rapid as when both α and β constituents are present.[6] Several of the samples of Muntz-metal sheathing, which were heat treated (see below) previous to subjecting them to conditions favorable for corrosion, were heated strongly enough so that zinc

[6] Second Report of Corrosion Committee, Jour. Inst. Metals; 1913.



a

b

FIG. 11.—*Method of dezincification*

The material was quenched after heating to 675° C. The β crystals are attacked most readily along certain planes arranged approximately in parallel sets in any individual crystal and resembling twinning planes. The material was thin sheathing and the attack was at right angles to the surface photographed. (×500.) Etching, concentrated ammonium hydroxide and ammonium persulphate.

was volatilized from portions of the surface, leaving a layer of α. This layer was in every case free from dezincification during the course of the experiment and served as a protective covering for the α–β alloy beneath. One of the samples of condenser tubing described illustrates the comparative freedom of α from attack. That the attack of the α does not follow that of the β at the same rate in all corroded samples is very evident from the types described. In the case of the corroded sheathing, the α is intact and apparently little changed even after seven years' exposure to sea water, while in others a few months' exposure disintegrates both constituents; the attack of the α very closely follows that of the β in such cases.

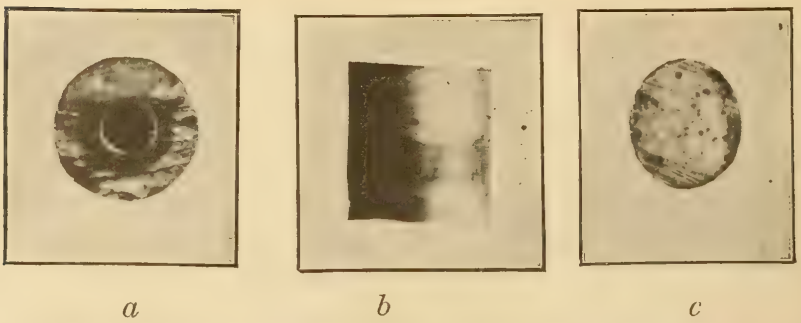
2. CONTACT WITH ELECTRONEGATIVE SUBSTANCES

If a sample of Muntz metal is in intimate contact, while immersed in an electrolyte (e. g., solution of sodium chloride), with a strongly electronegative metal (i. e., more electronegative than the α or β constituents), dezincification of those portions of the brass which is in immediate contact with the other metal will readily occur. As part of the study of the material of type 1, samples of the unchanged metal of the center were placed in contact with copper, others with steel, in a 5 per cent solution of sodium chloride. This electrolyte was chosen since this type of corrosion usually occurs in sea water. The copper readily induces dezincification, evidences of the attack showing after 12 hours' exposure, but only at or very near the point of intimate contact (Fig. 12*a* and *b*.) The attack is not general over the entire surface of the brass sample. No dezincification of the brass occurred in the case of the brass-iron couple. Although intimate contact with the proper substances will induce and accelerate the corrosive attack of brass, in none of the types previously described can this condition be assigned as the principal cause of the attack.

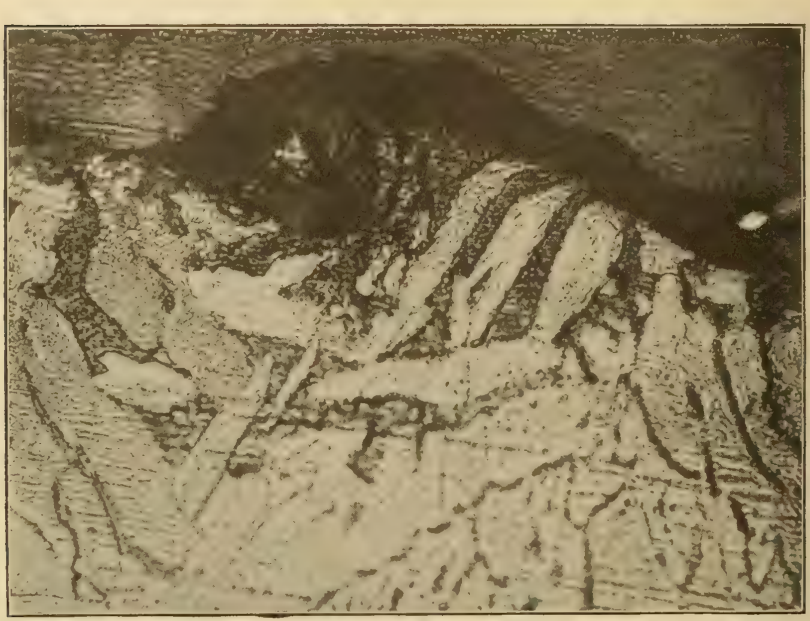
3. ACCELERATING EFFECT OF THE PRODUCTS OF CORROSION

The accelerating effect of deposits of basic zinc chloride formed on the surface of the corroded specimen by the corrosion of the brass, upon the further attack of the metal has been known for some time and has been previously described.[7] The exact way in which this acceleration occurs, however, is not clear, as yet. The basic zinc-chloride deposits have been described by some as

[7] C. H. Desch, Physical and Mechanical Factors in Corrosion, Jour. Faraday Soc.; 1915. (See, also, footnote 1.)



a *b* *c*



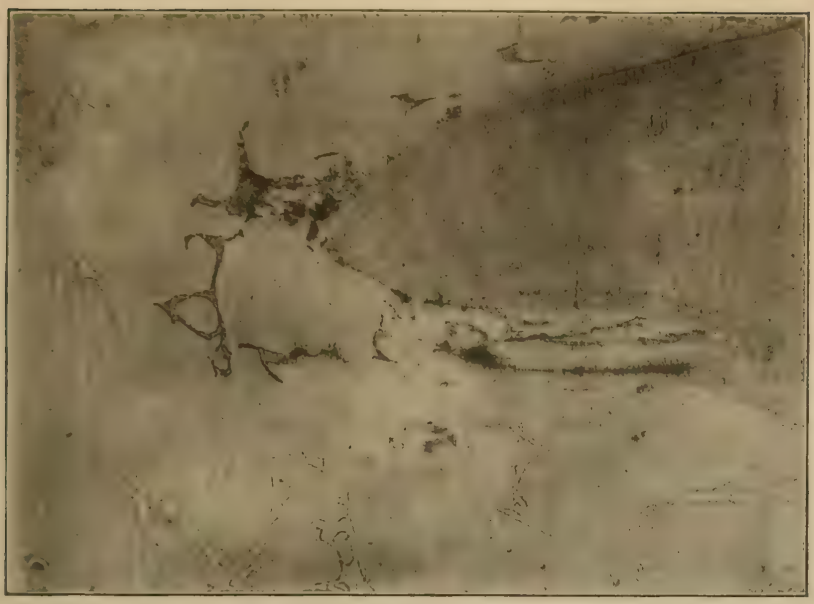
d

FIG. 12.—*Illustration of various conditions affecting dezi.. ification*

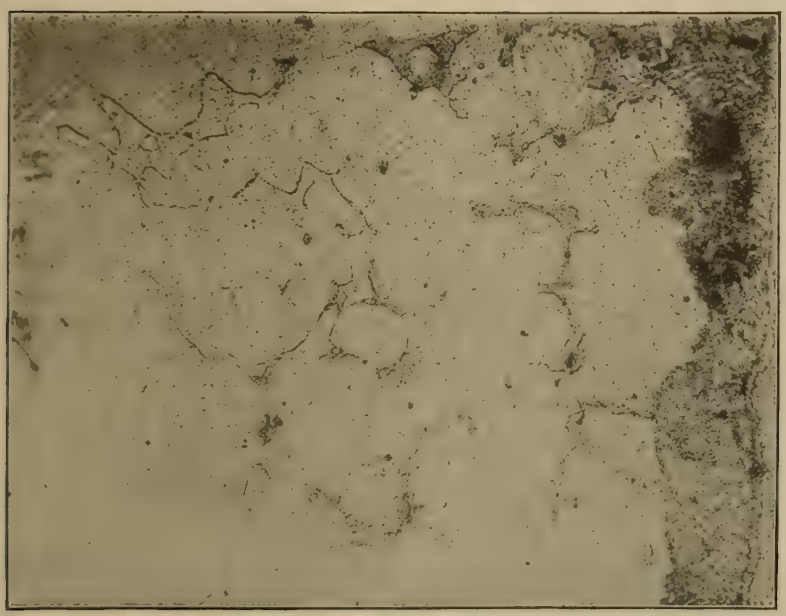
(*a–b*) Samples of Muntz metal which were in contact with copper while immerse.. 'n sodium chloride solution. In *a* the wire was inserted in the central hole; in *b* it was wrapped a.ound the sample. The attack is immediately adjacent to the copper wire. (×2).

(*c*) Muntz metal sample which has been immersed in 5 per cent sodium chloride solution. The dark spots are corroded areas which formed beneath adhering deposits of basic zinc chloride. (×2.) unetched.

(*d*) Cross section of one of the spots shown in *c*. (×500.) Etching, ammonium hydroxide and hydrogen peroxide. The dark band is the basic zinc chloride deposit which accelerated the attack of the metal beneath. A copper layer, shown in the upper two corners, was deposited in the sample to protect the edge of the specimen during the polishing.



a



b

FIG. 13.—*Illustrations of different conditions affecting dezincification*

(*a*) Base of V-groove in stress-corrosion specimen (No. 11, Table 2). The sample was nickel-plated and then copper-plated to protect the edge during polishing. The β has been dezincified at the extreme base of the notch. (×250.)

(*b*) Sample of Muntz metal dezincified by heating in molten zinc chloride. Both α and β are completely attacked in the surface layer, an intermediate layer in which the β only, has been dezincified separates this portion from the uncorroded part. (×250.) Etching for both *a* and *b*, concentrated ammonium hydroxide and ammonium persulphate.

acting "catalytically," by others as being strongly electronegative toward both the α and β constituents and thus inducing dezincification in the same way that copper does. Heavy deposits of basic zinc chloride and carbonate were observed on the inside of the condenser tubes and on the outer or exposed surface of the sheathing. In type 1 (wrought bolts used for attachment of a boat keel), though no pronounced deposit on the outside was found, the "copper" coating was observed to be impregnated with a similar substance. The deterioration of the metal directly adjacent to the deposits is in nearly every case entirely complete; that is, both α and β are attacked. The degree to which the metal is attacked decreases with the distance from these deposits. In the examples described below (secs. 4 and 5), closely adhering hard, smooth specks of white basic zinc chloride were often found on the surface of the specimen when allowed to stand in the sodium-chloride solution. The metal immediately beneath such deposits was invariably in the red corroded condition. Fig. 12 *c* and *d* illustrate the appearance of such corroded samples.

4. EFFECT OF HEAT TREATMENT

It has been suggested that the differences shown by different lots of Muntz metal in their resistance to this type of corrosion is to be attributed to unavoidable variations in the heat treatment such samples have received,[8] and that thorough annealing of the alloy at 650° to 800° C will prevent the preferential attack of the β, or zinc-rich, constituent. A series of samples of new sheet Muntz metal of the following composition were annealed for periods varying from 30 minutes to 4 hours; one series at approximately 370° C (360–373° C), the second at approximately 640° C (625–655° C):

	Per cent
Copper	61.35
Lead	.46
Tin	.16
Iron	.20
Zinc (difference)	37.83

These two annealing temperatures were chosen so as to illustrate the possible effect of heating below or above the transformation which occurs in the β constituent at 470° C. The samples were then immersed in 5 per cent solutions of sodium chloride for a period of 70 days, each sample being suspended

[8] Second Report of Corrosion Committee, discussion by Sir Gerard Muntz, Jour. Inst. Metals, X, 1913, p. 101.

by silk thread, proper care being taken to avoid contact with each other or with the glass sides of the container. No effort was made to regulate the temperature of the solution; it varied between 12° C and 20° C. At the close of this period a microscopic examination of cross sections of the samples showed that each one had been attacked to a slight degree. This attack, which is confined to the β constituent, was not general over the entire surface but was confined to small local centers. Each sample showed closely adhering white specks of basic zinc chloride; the metal under such speck showed a dezincification of the β constituent to an average maximum depth of 0.39 mm (0.0156 inch). The depth to which this attack of the β constituent had penetrated varied from 0.31 mm (0.0124 inch) to 0.05 mm (0.0020 inch), but apparently bears no relation to the previous heat treatment of the sample but rather to the character of the surface, a slightly roughened or pitted surface forming a much better support for holding the zinc-chloride deposits, which form from the slight general attack of the metal when first immersed, than a smoother one does. The samples heated for two and four hours at the higher temperature, 640° C, had lost some of the zinc by volatilization, so that much of the surface layer is consisted of but the α constituent. No attack of such portions was observed.

Samples of the same material used above were quenched in water after heating to a temperature of 690° C. At this temperature both constituents, α and β, still persist (Fig. 9). The attack in this case was more rapid, the β having been attacked to a depth of 0.125 mm (0.005 inch) after 13 days' immersion in 5 per cent sodium-chloride solution.

The obvious conclusion to be drawn is that thorough annealing of the metal is not sufficient to entirely inhibit the selective corrosion of the material. The accelerating influence of the adhering deposits of the basic zinc chloride, however, appears to be a necessary condition for such an attack of the annealed metal.

5. TEMPERATURE

Practical cases of the effect of temperature upon this type of corrosion have been brought to the attention of this Bureau. One striking example is that of the corrosion of the tubes of a condenser using sea water. The outlet pipe, in which the water was always considerably warmer than the incoming stream, corroded badly enough to require replacement several times

while the inlet pipe was still intact and in service. The effect of temperature upon corrosion of similar material has also been studied by Bengough.[9]

6. STRESSES

The appearance of two of the types described (1 and 4) suggest the possible accelerating influence of the stresses to which these samples were subjected as one of the causes contributing to corrosion of this type. To illustrate this, a series of specimens were subjected to tensional stress while immersed in a 5 per cent solution of sodium chloride. The specimens were turned down to a diameter of approximately one-fourth inch, a very narrow V notch was then cut so that the diameter at the point of the notch was reduced to one-eighth inch. The purpose of the experiments was to see whether along the line of maximum stress—that is, the base of the V groove—the metal corroded more uniformly and readily than elsewhere on the same specimen. The samples were removed periodically from the solution and examined to make certain that no deposits of basic chloride had formed within the groove which might thus accelerate the attack at that point. Fig. 14 shows the method of the set-up.

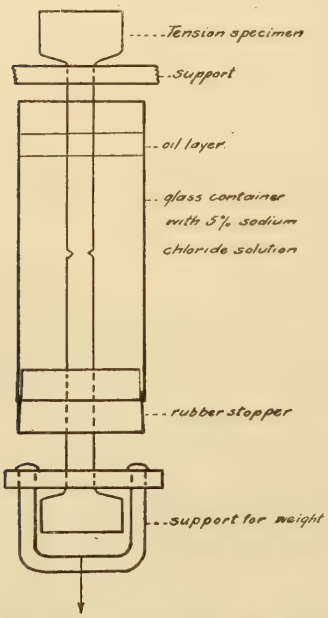


FIG. 14.—*Arrangement for applying tensional stress while specimen was immersed in sodium chloride solution*

The specimen is one-eighth inch in diameter at the base of the groove.

The material used was of the α–β type of structure and of the following composition:

	Per cent
Copper	62.26
Tin	.18
Lead	.00
Iron	.00
Zinc (difference)	35.56

The samples were used both in the cast condition and after annealing at approximately 520° C. A determination of the mechan-

[9] Second Report of Corrosion Committee, Jour. Inst. Metals; 1913.

ical properties of the material as cast and as annealed gave the following results:

Sample	Cast	Annealed
Ultimate strength, pounds per square inch	37 800	27 200
Proportional limit, pounds per square inch	5 000	7 500
Reduction of area, per cent	34.2	35.7
Elongation, 2", per cent	39.5	25.0
Fracture	(*a*)	(*b*)

a Irregular; lemon-colored spots. *b* Flaw at center.

Table 2 gives the results obtained after immersion for varying periods in 5 per cent sodium-chloride solution, the sample being under tension, which was maintained constant for the specimen throughout the period. The temperature was that of the room, which varied between 10 and 18° C (approximate).

TABLE 2

Corrosion of Muntz Metal While Stressed in Tension

Specimen	Stress	Period	Physical state of material	Results *a*
	lbs. in.^{2}	Days		
3a[b]	6 400	50	As cast	No dezincification at base of V groove.
3b[b]	16 000	17	do	β is attacked in base of groove to a depth of 0.25 mm.
4	6 400	59	do	No dezincification in groove.
5	9 600	10	Annealed; 50 minutes at 515° C and cooled in air.	No dezincification in groove. A network of very fine hairlike intercrystalline cracks opened up in the metal. The metal immediately adjacent to the cracks was dezincified, both α and β being attacked.
6	12 800	35	do	The β has not been attacked in the groove.
10	9 600	60	do	β was attacked in base of groove to a depth of 0.25 mm. The α was slightly attacked.
11	12 800	40	As cast	Dezincification of the β to a depth of 0.16 mm at the base of the groove occurred (Fig. 13*a*).
12	9 600	58	Quenched from 685° C in cold water.	No dezincification was observed in the groove.

a The slight dezincification induced by the rubber stoppers or by small adhering specks of basic zinc chloride on the cylindrical surface of the specimen is not included here. Fig. 13*a* illustrates this attack.
b 3a and 3b are the same specimen; after 60 days the load was increased to 16 000 pounds; that is, above the proportional limit.

The tension tests made on samples of the material used as well as the fine cracks noted in some of the samples (some were discarded entirely for this reason) show that the material was not very uniform. The results of the tension tests are to be regarded as approximate only for the material

Though the results are not to be regarded as conclusive, they are strongly suggestive that brass of the α–β type highly stressed is more prone to selective corrosion than when not so, particularly when the stress is highly localized; for example, at the base of a fine hair crack or a narrow groove. Of the eight samples used, the four which showed dezincification were all stressed above the proportional limit. Both specimens 3*a* and 4, which were stressed below the proportional limit, failed to show any trace of attack even after 60 days' exposure. It should be noted, however, that all which were stressed above the proportional limit were not alike in developing dezincification. Specimen No. 12 (9600 pounds load), which was quenched, is not strictly comparable with the others in that the mechanical properties are not necessarily the same as those in the cast condition. Also, this sample lacked the decided duplex structure shown by the others; this may be due to a slight difference of chemical composition. No adequate reason can be assigned for the failure of specimen No. 6, which was loaded above the proportional limit to develop dezincification. The change induced in the surface layer by the machining which the specimens received may be suggested as one of the possible contributing causes. The surface flow of the constituent in some cases is sufficient to entirely cover the β and thus protect it from the attack of the electrolyte. The results of the stress-corrosion tests, while not entirely conclusive, are in keeping with the general appearance and service behavior of some of the types described (1 and 4, Table 1).

Metal which has been quenched from a relatively high temperature may be readily shown to be internally stressed, due to the different rates of cooling of the outer layers relative to the interior, the differential rate of expansion of the different constituents, if more than one is present, etc. The peculiar manner in which the crystals of Muntz metal are corroded when the specimen has been quenched (Sec. III–4, above) suggests that this difference as compared with the manner of attack in the annealed metal may be induced by the stressed condition of such crystals resulting from the extremely rapid rate of cooling.

7. ACTION OF "FLUX" ON MUNTZ METAL

Muntz metal which has been cleaned by the use of zinc chloride, ammonium chloride, etc., often used as a "flux" for cleaning metal surfaces, by heating the metal and rubbing with a swab saturated

with a solution of the substance used often assumes a red color. That this reddening of the surface is a particular case of dezincification is shown by microscopic examination of cross sections of the metal taken through such reddened areas. Fig. 13*b* shows the result of heating a sample of Muntz metal in molten zinc chloride; in the surface layer both α and β are attacked, a thin intermediate layer in which only the β is attacked precedes the attack upon the α. The suggestion is offered that metal which has been so cleaned and, consequently, which shows dezincification to a slight extent may be, perhaps, more readily attacked in service, particularly if the metal contains any slight surface cracks and depressions which might serve to hold the chloride and thus act as centers for later corrosion in service.

V. SUMMARY

1. The deterioration of Muntz metal by selective corrosion is illustrated by four types, including tubing, sheets, and forgings. The metal becomes red in color, very weak, and brittle by this type of corrosion, which takes place when the piece is exposed to some electrolyte.

2. The metal has a duplex structure, one of the constituents, β, being very much higher in zinc than the other, α. In all cases, the selective corrosion consists of a preferential attack of the zinc-rich constituent and the formation of a porous "copper" mass which fills the network of holes previously occupied by the β. This attack may or may not be followed by that of the second constituent.

3. The rate at which the α phase is attacked is variable. The attack of this constituent may follow almost immediately that of the β or may be indefinitely delayed.

4. A state of dezincification may result in α brass under certain conditions, although the method of attack as revealed by the microstructure is different.

5. The line of demarcation between attacked and unattacked portions is very sharply defined. The action is not a gradual one, but the change is an abrupt and complete one even within the individual β crystals.

6. One of the most important conditions favorable to this type of corrosion, which occurs commonly while the metal is immersed in sea water, is the accelerating effect of the closely adhering deposits of basic zinc chloride resulting from the attack of the metal. Other influences which may accelerate the rate of attack

are contact with substances more electronegative than either the α or β constituents, an increase of temperature, and the effect of stresses to which the material may be subjected while in service.

7. Thorough annealing of Muntz metal does not entirely prevent the selective corrosion of the β constituent.

WASHINGTON, June 4, 1917.

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EFFECT OF THE SIZE OF GROG IN FIRE-CLAY BODIES

BY

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Bureau of Standards

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By F. A. Kirkpatrick

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I. INTRODUCTION

In those industries which use crushed and ground raw materials in forming bodies by means of a cementing action of some sort the size of the particles plays a most important rôle. This may be in many instances the main factor controlling the desired properties in the body. This is nowhere more true than in the ceramic industries, where in compounding bodies the manufacturer is compelled to use materials from the size of pebbles down to the dispersoid and emulsoid (colloidal) states. All present evidence tends to show that in disperse systems the size of particles which we can not now measure has as much effect upon the properties of certain materials as have the larger sizes which we are able to measure. In no other way is it possible to account for the great

differences in cementing power exhibited by fine-grained bond clays and other fine-grained materials. In practice the cementing action takes place at temperatures from zero to that of the electric arc, depending upon the nature of the process, and is due to many different chemical reactions. In the present work the bonding power of mixtures composed of raw clay and calcined clay is determined after these bodies have been heated to 110° C and to 1250° and 1300° C.

II. LITERATURE

The literature upon this subject is confined mostly to investigations of mortars and concretes. Rene Feret, chief of the Laboratory of Bridges and Roads at Boulogne-sur-Mer, France, has made an extensive investigation of the effect of the size of grain of sand upon the properties of cement mortars.[1] In this work the sands were separated into three sizes as follows:

Designation	Range of size of particles	Approximate screen sizes, Tyler standard
	Inch	Mesh
G	0.20 –0.079	4–10
M	.079– .02	10–30
F	.02 –dust.	30–dust

These three sizes were combined in all possible proportions and made up into Portland cement mortars and various properties determined. The results were shown graphically by means of triaxial diagrams as illustrated in Fig. 1. The lines within the triangle were drawn through points representing mortars having the same strength. The strongest bodies contained sand of about 80 parts *G*, 20 parts *F*, and a small amount of *M*. It should be noted that Feret worked with mortars only and not with concretes

Fuller and Thompson [2] have studied the effect of the size of materials on concrete, where the conditions are different from those in mortars. They recombined the different sizes of materials, not by means of triaxial diagrams but by the use of analysis curves. By this method any number of different sizes can be accurately combined to form a mixture of any desired granular composition. One of the most important conclusions was that concrete having

[1] Sur la compacité des mortiers hydrauliques, Annalen des Ponts et Chaussees, Memoires et Documents, 4, pp. 1–164; 1892–2.

[2] The Laws of Proportioning Concrete, Trans. Amer. Soc. Civil Engrs., 59, p. 67; 1907. Also Concrete Plain and Reinforced, Taylor and Thompson.

the highest density and highest strength possessed an analysis curve which consisted of an ellipse and a straight line or of a parabola. The method is illustrated in Fig. 2. The curve designated "Parabola" is the analysis curve of the strongest concrete. Materials Nos. 1, 2, 3, and 4 have been so combined that the mixture has a curve very close to the parabola, as indicated by the dotted line.

After an extended investigation, Wig, Williams, and Gates[3] concluded that the law of greatest strength given by Fuller and

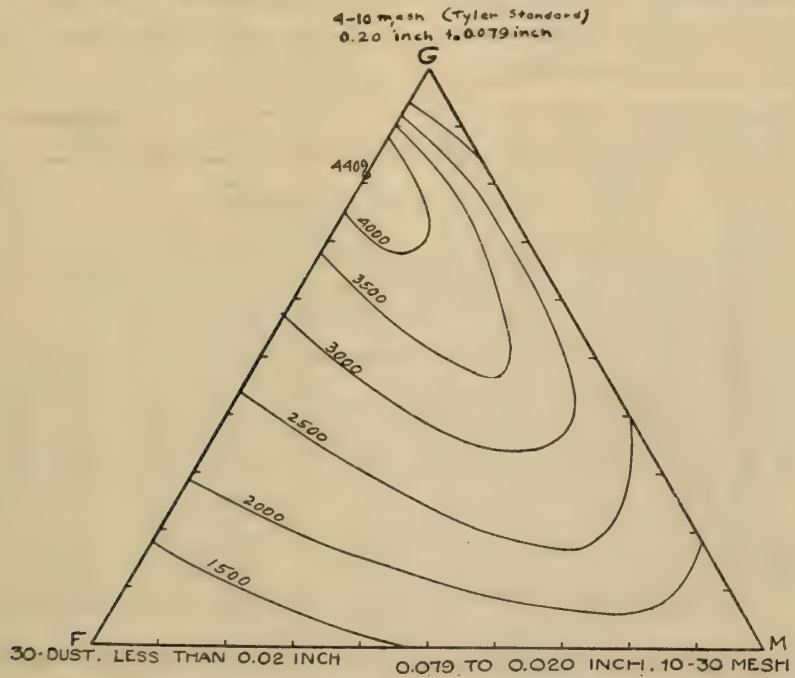

FIG. 1.—*Relation between size of sand and compressive strength in pounds per square inch of 1:3 (by weight) mortars after nine months in air and three months in sea water. After Feret. From Concrete Plain and Reinforced (p. 146), Taylor and Thompson*

Thompson is not general and that there exists no maximum curve applicable to all concretes and mortars.

It should be noted that the results of the above investigations could be expected to throw light upon the question of the size of grain in fire-clay bodies in the unburned state only, since in the burned state other factors, such as fusion or vitrification, exert the controlling influences upon the properties.

The recorded work on the effect of fineness of materials on the properties of bodies in the burned state has to do mostly with

[3] Strength and Other Properties of Concrete as Affected by Materials and Methods of Preparation, B. S. Technologic Paper No. 58

vitreous products as porcelain, china, etc. The effect of the size of grog in fire-clay bodies, however, was studied by Fulton and Montgomery [4] using bodies made up of 50 per cent St. Louis fire clay and 50 per cent grog by weight. They prepared five sizes of grog, using all material passing through the sieves of 6, 14, 35, 100, and 200 mesh. They found that the modulus of rupture in the raw state increased from 6 to 100 mesh grog, then decreased with 200 mesh, showing that the very fine nonplastic gave a low strength. In the burned state, strength increased with decrease of grog size up to cone 15. At this temperature, porosities of 6, 14, and 35 mesh bodies were 10 to 13 per cent, while those of 100 and 200 mesh bodies were 5 to 6 per cent.

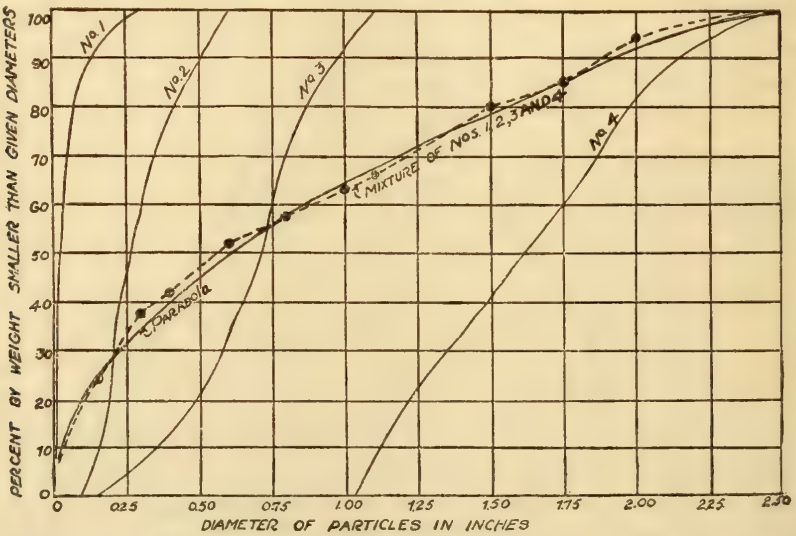

FIG. 2.—*Method of proportioning a graded mixture. From Concrete Plain and Reinforced (p. 786), Taylor and Thompson*

In view of the fact that so little work had been done along this line, it was considered advisable to undertake an investigation of the effect of the size of grog on some properties of fire-clay bodies. On account of the fact that the grog could be separated into a great many portions of different sizes and recombined in an infinite number of proportions, the present work could hope to cover only a limited field of practical grog sizes.

This work was begun by G. H. Brown and H. G. Schurecht in 1915 and completed by the writer in 1916–17 along the same lines as originally planned. Although the investigation was intended as a study of sagger bodies, a more general application of the results can be made.

[4] The Effect of Grog in Fire Clay Bodies, Trans. Amer. Cer. Soc., 17, p. 409

III. METHODS

1. GENERAL PLAN

The general plan of procedure consisted of the separation of grog into different sizes, recombining these in arbitrary proportions, adding an equal weight of plastic fire clay and molding into small bars for testing. As stated in the introduction, there are two principal methods of recombining the separated portions—first, by means of triaxial diagrams; second, by means of analysis curves. The first method was adopted, since it was obvious that the second would be of value only for bodies in the raw state. Strength in the burned state increases with surface factor below the temperature where overburning begins and the analysis curve for maximum strength would be a straight line perpendicular to the size axis at the ordinate representing the smallest size obtainable.

2. PREPARATION OF GROG

The grog was made by crushing high-grade fire brick, which was composed of about 50 per cent flint fire clay, in a wet pan. The grog was screened through sieves with a power shaker and separated into the following sizes: 4 to 8 mesh, 8 to 12, 12 to 20, 20 to 40, 40 to 80, 80 to dust. Each sized portion was thoroughly mixed by means of shoveling. Mechanical analyses were made of each portion with Tyler standard screens. The sizes of the screens used were as follows:

Mesh	Size of opening	Mesh	Size of opening	Mesh	Size of opening
	Inch		Inch		Inch
4	0.200	14	0.046	80	0.0069
6	.131	20	.033	150	.0041
8	.093	30	.0198	200	.0029
10	.072	40	.0150	300	.0017
12	.054	60	.0087		

The analyses of the separate portions were as follows:

Mesh of screen	Mesh of screen	Per cent passing	Mesh of screen	Mesh of screen	Per cent passing
4–8	4–6	49.4	40–80	40–60	52.7
	6–8	50.6		60–80	47.3
8–12	8–10	36.9	80–dust	80–150	37.4
	10–12	63.1		150–200	15.8
12–20	12–14	26.6		200–300	19.0
	14–20	73.4		Through 300	27.8
20–40	20–30	44.8			
	30–40	55.2			

3. PREPARATION OF BODIES

All bodies were of the composition 50 per cent grog and 50 per cent clay by weight. The clays were ground to pass a 20-mesh screen. The bodies were made up in seven triaxial series having the following grog components and clay composition:

Series number	Size of grog (mesh)	Clay
1	4–8, 8–12, 12–20	Plastic fire clay.
2	8–12, 12–20, 20–40	Do.
3	12–20, 20–40, 40–80	Do.
4	20–40, 40–80, 80–dust	Do.
5	4–20, 20–80, 80–dust	Do.
6	4–20, 20–80, 80–dust	Equal parts plastic fire clay and Georgia kaolin.
7	4–20, 20–80, 80–dust	Illinois kaolin.

The 4 to 20 mesh grog was composed of equal parts of 4 to 8, 8 to 12, and 12 to 20 sizes. The 20 to 80 grog was made up of equal parts of 20 to 40 and 40 to 80 sizes. Each series contained 16 bodies designated by letters and having the grog composition shown in Table 1.

TABLE 1

Letter	Per cent A	Per cent P	Per cent M	Letter	Per cent A	Per cent P	Per cent M
A	100	.....	.....	I	33⅓	66⅔	.....
B	66⅔	.....	33⅓	J	20	20	60
C	66⅔	33⅓	.....	K	20	40	40
D	60	20	20	L	20	60	20
E	40	20	40	M	.....	.....	100
F	40	40	20	N	.....	33⅓	66⅔
G	33⅓	.....	66⅔	O	.....	66⅔	33⅓
H	33⅓	33⅓	33⅓	P	.....	100	.....

The clay and grog were thoroughly mixed dry by shoveling and pugged in a wet pan. The plastic mass was left standing at least two hours to allow the grog to absorb moisture. Briquettes 1 by 1 by 7 inches were molded by hand in a brass mold. This size was chosen because it had proved satisfactory for similar tests. The use of several sizes would have been too time consuming. Moreover, the results obtained would themselves determine whether or not the proper size had been used.

4. PROPERTIES OF RAW BODIES

Two properties of the mixtures in the raw state were determined—strength and porosity. Modulus of rupture was chosen as a measure of strength, since this was found by Bleininger and

Howat[5] to give more uniform results than compressive or tensile-strength. Merriman's discussion of beams in Mechanics of Materials shows that bars under transverse load are subject to forces of shear, tension, and compression and that the values of modulus of rupture, or flexural strength, lie between those of tensile strength and compressive strength. Thus the modulus of rupture results from a combination of these three forces, and for our present purpose gives a better all-around idea of strength than any one of the three. For these determinations, briquettes were air-dried at least three days, dried at 65° C for one day, and finally at 110° C for two days. They were broken in the transverse test machine described by the above writers.

The formula used for calculation of the modulus of rupture was as follows:

$$M = \frac{3\,Fl}{2\,bd^2}, \text{ where}$$

M = modulus of rupture in pounds per square inch;
F = force applied in pounds;
l = length between supports in inches;
b = width of bar in inches;
d = depth of bar in inches.

The distance l was 5½ inches; b and d were each about 1 inch, and were measured to hundredths of an inch. Seven bars of each mixture were tested and the average modulus of rupture calculated.

For the determination of porosity, briquettes were dried at 110° C for 1 day, weighed, immersed in kerosene, and placed in a cylinder under reduced pressure (about 0.2 atmosphere) for 12 hours. They were then weighed suspended in kerosene and in air. Four test pieces of each body were used.

5. PROPERTIES OF BURNED BODIES

For the determination of properties in the burned state, briquettes were given three different heat treatments: Cone 10, 1200° C; cone 12, 1250° C; cone 14, 1300° C. A gas-fired test kiln was used, the rate of rise of temperature being 25° C per hour. The final temperature was maintained for 2 hours.

The properties of the burned bodies determined were strength, porosity, volume shrinkage, and resistance to sudden temperature

[5] The Compression, Tensile and Transverse Strength of Some Clays in the Dry State, Trans. Amer. Cer. Soc., 16, p. 273.

changes. The modulus of rupture was used as a measure of strength. In order to decrease the time consumed in laboratory work, the 3½-inch pieces obtained by breaking the raw bars were used in the burned state for these tests with a 2-inch span. The bars were broken in a 10 000-pound hand-power Olsen machine and the modulus of rupture calculated in the same manner as given for raw bodies. The question has arisen as to whether the 2-inch length of span is too short and the values obtained for modulus of rupture too high due to their including a proportion of the shearing strength, which may be higher than flexural strength. In the absence of sufficient evidence no conclusion can be reached. It may be of interest to note that Fulton and Montgomery in the work quoted in footnote 4 (p. 6), using St. Louis fire-clay bodies and a 4-inch span, obtained values of modulus of rupture up to 6622 pounds per square inch, while the highest in the present work was 5373 pounds per square inch for the 80 to dust grog body. A standard size of bar should be used for this work. Bars 1 inch square and long enough for a 4 or 6 inch span have proven satisfactory. In regard to the results here presented, it may be said that they afford a sufficientiy accurate means of comparison of strength of the bodies. The average difference from the mean value was about 10 per cent, as low a value as could be expected for fire-clay bodies.

Determinations of porosity were made in the same manner as for the raw bodies, except that water was used instead of kerosene. Volume shrinkage was determined by measuring the volume of the test pieces in a volumenometer before and after burning. Two briquettes of each kind were used.

In order to determine the loss of strength due to sudden temperature change, briquettes previously burned to cone 12 were heated five times to 600° C and quenched in ice water after each heating. Six test pieces of each kind were used. The modulus of rupture was then determined with a 2-inch span. The strength after treatment expressed as a percentage of that before treatment afforded a means of comparison of the value of the bodies in repeated heating.

Some manufacturers who use refractory brick for checkerwork demand that these brick shall not fail upon being heated 30 times to 1000° C and quenched in cold water for 1 minute after each heating. On account of the importance of this test, it was desired to determine the effect of the size of grog upon the dura-

bility of bodies subjected to such treatment. Bars 1 by 1 by 7 inches previously burned to cone 12 were heated in a gas furnace to 1000° C in from 2 to 4 hours and quenched in running water at about 15° C after each heating. The bars were immersed for 15 seconds. After this length of time they were still at a red heat in the center and absorbed no water; hence, were perfectly dry when replaced in the furnace. The number of treatments which the bars withstood before breaking in two was used as a means of comparison of their durability under the conditions of the test. The broken pieces were reheated many times, but a criterion of final failure could not be devised for such small pieces and no results of value were obtained.

IV. RESULTS OF TESTS UPON BODIES CONTAINING ONE SIZE OF GROG

Before studying the results obtained by recombining the grog portions, it will be of interest to examine the data for bodies containing the single sizes. In Fig. 3 is shown the relation between temperature of burning and porosity of these bodies and of the clays. The corresponding values are given in Table 2. The method of making these determinations and the meaning of the curves is given on page 12 of this Bureau's Technologic Paper No. 79, by Bleininger and Schurecht on European Plastic Fire Clays. It is sufficient to repeat that the amount of pore space and the rate of change of this amount in burning are accurate indications of the vitrification temperature range, of the temperature of overburning, and hence of the refractoriness of the materials.

TABLE 2

Porosity of Clays and Bodies

Temperature, °C	Fire clay	Georgia kaolin	Grog body					
			4–8	8–12	12–20	20–40	40–80	80–dust
1150	27.70	45.30	25.72	26.70	27.85	29.20	29.75	29.72
1200	20.19	44.70	24.81	25.20	27.15	28.03	29.40	28.53
1230	14.08	39.28	23.59	24.43	26.50	26.65	27.90	26.63
1260	11.32	32.90	22.45	22.87	25.35	25.90	26.75	24.01
1290	9.58	29.48	22.40	22.80	24.35	24.10	26.12	23.25
1320	7.65	21.60	21.08	21.90	22.85	22.95	25.23	20.45
1350	4.19	19.05	17.75	18.60	19.05	18.90	21.21	14.75
1380	1.70	15.75	16.88	18.50	17.96	17.35	19.70	10.65
1410	1.41	15.88	16.24	17.49	17.62	16.90	17.90	10.51
1440	2.69	14.48	15.35	17.09	16.91	15.50	16.27	8.36

As the curves of Fig. 3 show, the bodies possess quite different rates of vitrification. At 1150° C the porosity of all the materials was from 25 to 30 per cent with the exception of the Georgia kaolin, which was 45.3 per cent. These are characteristic values

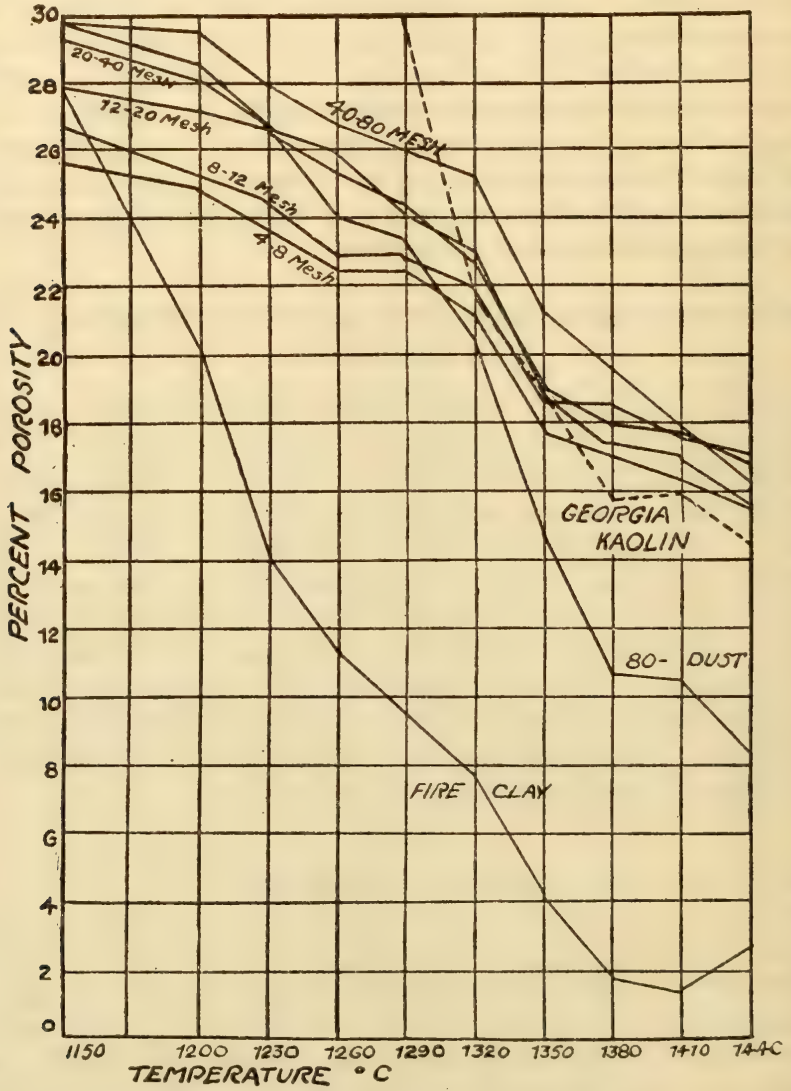

FIG. 3.—*Relation between porosity and temperature of burning of clays alone and of bodies containing grog*

for the types of clays represented. The Georgia kaolin had a high rate of vitrification below 1380° C at which temperature its porosity was only a little lower than that of the fire-brick bodies. Hence, when added to fire-brick mixtures the kaolin decreases the strength,

since it decreases the amount of fused or vitrified material in the brick. The fire clay had an average rate of decrease of porosity amounting to 5.1 per cent per 30° from 1150° C to 1230° C and 2.5 per cent per 30° from 1230° C to 1380° C. At 1380° C overburning began, due to the formation of a vesicular structure.

The addition of an equal weight of grog of any of the sizes indicated from 4 to 8 mesh to 40 to 80 mesh lowered the rate of decrease of porosity to an average of about 1.25 per cent per 30° C. That is, the refractoriness of the clay-grog bodies was much greater than that of the fire clay and the effect of overburning was eliminated. It is noted, however, that at the higher temperatures the 40 to 80 mesh body has a somewhat higher rate of vitrification and the 80 to dust body a much greater rate than have bodies containing coarser grog. In fact, the rate of decrease of porosity for the 80 to dust body from 1320° C to 1380° C was twice that of the fire clay; that is, the 80-mesh grog formed a dividing line between the coarse or slowly vitrifying and the fine or rapidly vitrifying grog in bodies made up with this especial fire clay. The fine grog offered more surface per unit volume for heat absorption and consequent fusion, and for solution by the fused portion of the clay. Another point of special interest is the fact that all of the curves except that for Georgia kaolin indicate a higher rate of vitrification between 1320° C and 1350° C than on either side of these temperatures. This may indicate the temperature at which a eutectic mixture begins to fuse. Stated in cones, the above range is approximately that from cone 12 to cone 14, since the draw-trial burn consumed less time than the other burns. As will be seen later, there was a great increase in strength of the bodies from cone 12 to cone 14, corresponding to the larger decrease in porosity within this range of heat treatment.

In Fig. 4 is given the strength-porosity curve for raw bodies. From 4 to 8 mesh to 40 to 80 mesh grog, strength increased with increase of porosity, this being due probably to cracks developed in drying. The size of the cracks decreased with decrease in size of grog. From 40 to 80 mesh to 80 to dust, strength decreased in the usual order with increase of porosity.

In Fig. 5 is shown the relation between surface factor and modulus of rupture in the raw and burned states. The surface factor was calculated according to the method suggested by Purdy [6] and includes the grog portion only. The strength

[6] The Calculation of the Comparative Fineness of Ground Materials by Means of a Surface Factor, Trans. Amer. Cer. Soc., 7, p. 441.

increased with increase of surface factor and with increase of temperature. As Fig. 6 shows, porosity in the raw and burnt

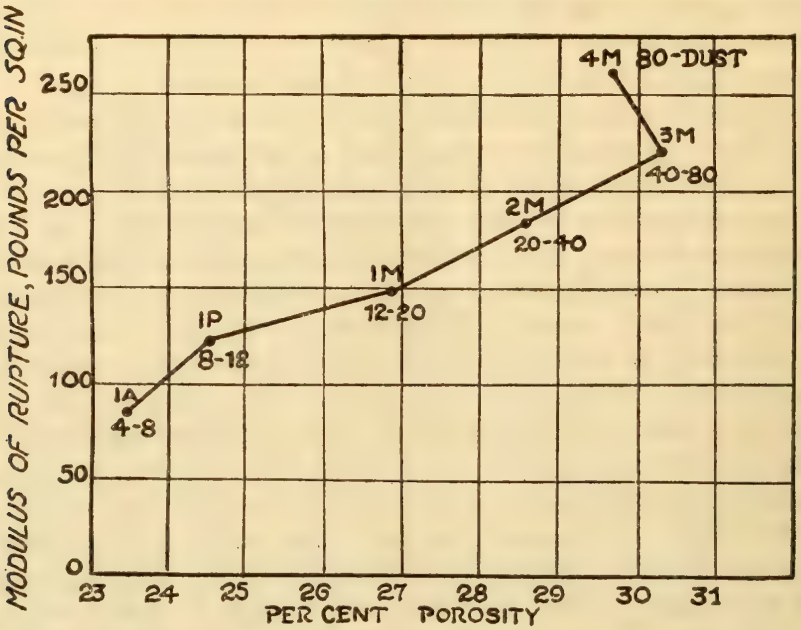

FIG. 4.—*Relation between porosity and modulus of rupture of raw bodies*

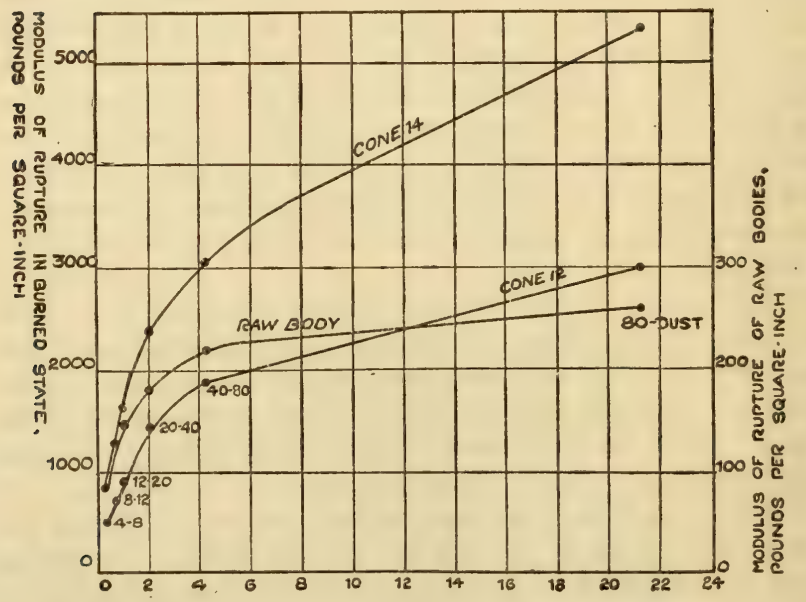

FIG. 5.—*Relation between surface factor and modulus of rupture*

states was a maximum in the 40 to 80 mesh body. The results from the quenching tests are given in Fig. 7. Bodies containing

the larger sizes of grog withstood the test best. The results for the single grog sizes are presented here briefly as a convenient

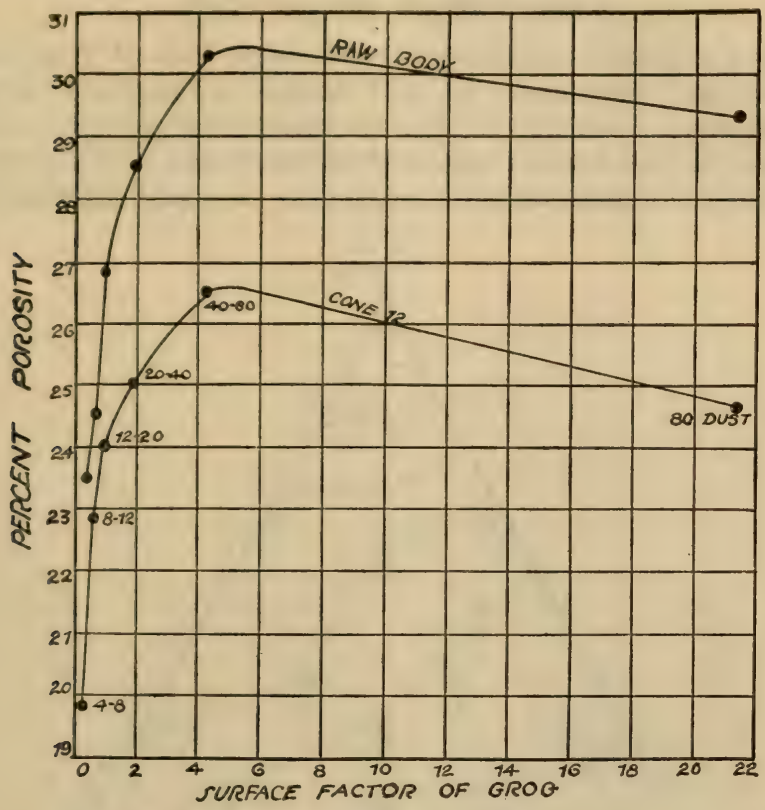

FIG. 6.—*Relation between surface factor and porosity*

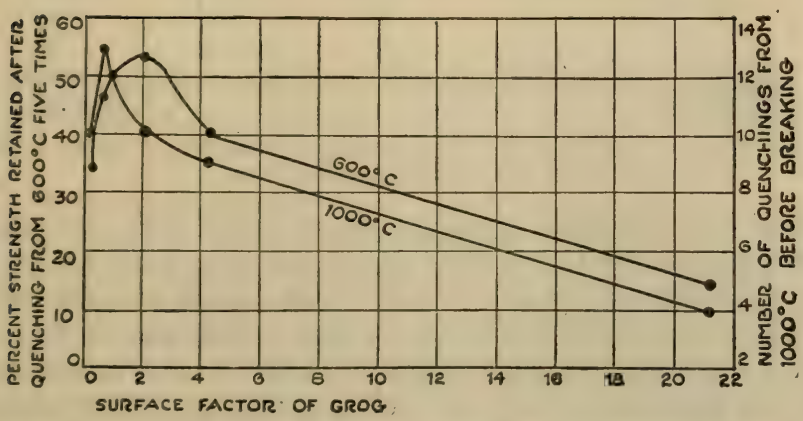

FIG. 7.—*Relation between surface factor and results of quenching tests*

means of comparison and will be included in the more detailed discussion of mixtures to follow.

V. RESULTS OF TESTS UPON BODIES CONTAINING MIXTURES OF GROG SIZES

1. PROPERTIES IN THE RAW STATE

(*a*) *Explanation of Diagrams.*—The single sizes of grog were recombined and made up into bodies as described under "Methods." Figs. 8 to 14 show the relation between grog composition and modulus of rupture of the raw bodies. This method of graphical representation of results may be briefly explained as

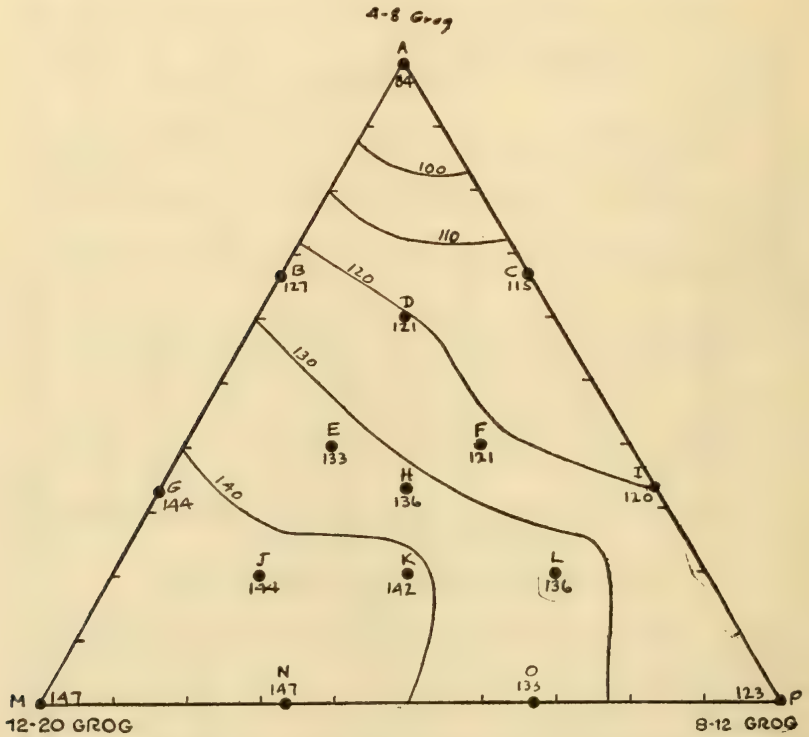

FIG. 8.—*Series 1. Relation between grog composition and modulus of rupture of raw bodies. Clay composition: All fire clay*

follows: The sum of the perpendicular distances from any point within the triangle to the three sides is the same and is equal to the perpendicular distance from an apex to the opposite side. This distance is called 100 or 100 per cent. Each apex represents a grog composition of 100 per cent of the kind of grog designated and the opposite side zero per cent. Hence, to determine the composition, the distance from the given point within the triangle to any side is observed. This is the per cent of material represented by the apex opposite the side chosen. Thus, the grog *J*

is composed of 20 per cent P, 20 per cent A, and 60 per cent M. Each side of the triangle is divided into 10 parts, as indicated by the dashes, but to avoid confusion these are not extended across the diagrams. The curved lines within the triangle are drawn through points representing the grog composition of bodies of equal strength. It is not necessary to consider the clay content of the bodies in the representation, since the per cent of clay is constant.

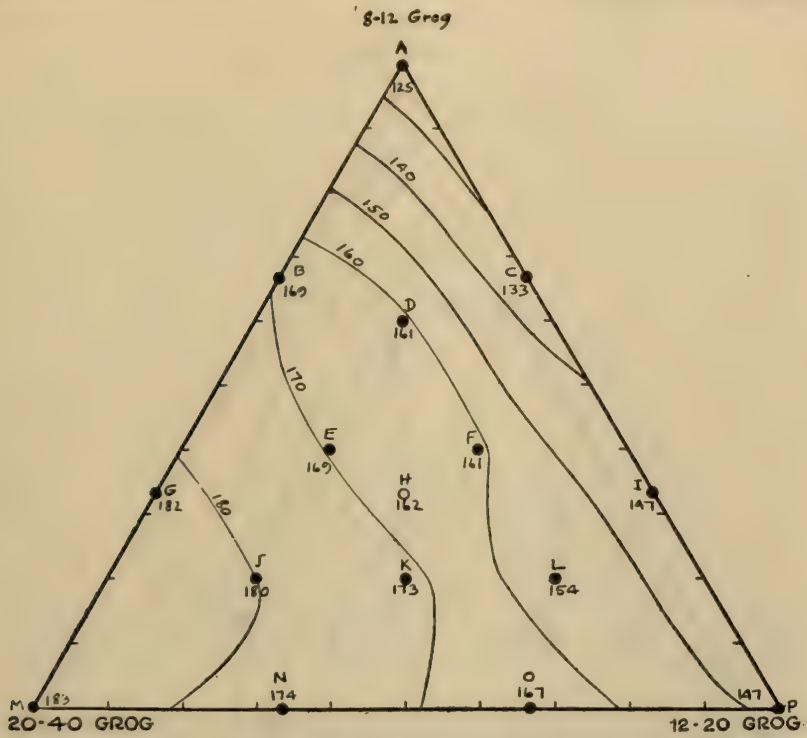

FIG. 9.—*Series 2. Relation between grog composition and modulus of rupture of raw bodies. Clay composition: All fire clay*

(*b*) *Analysis of Results by Means of Theory of Voids.*—In glancing over Figs. 8 to 14, one receives the impression of a set of topographical maps, each having its own peculiar arrangement of contour lines. In the present case we are dealing with iso-strength lines and the factors governing the shaping of their courses are not readily discovered. It is noted that the strength of the bodies increased with increase of porosity in series 1, 2, and 3, and with decrease of pore space in series 4. (See Figs. 4, 16, and 17.) The changes in porosity and strength in the first three series were not

coordinate and are explained as follows: Porosity increased because the larger particles were more dense than an equal weight of packed smaller sizes; also, as will be shown later, because the voids were increased by the mixture of sizes. Strength increased because the larger particles gave weaker bodies due to lack of bond and contact between clay and grog. This caused small cracks in drying, which decreased in size with decrease in size of grog. In series 4 no cracks appeared, bond was good, and strength decreased with decrease of porosity.

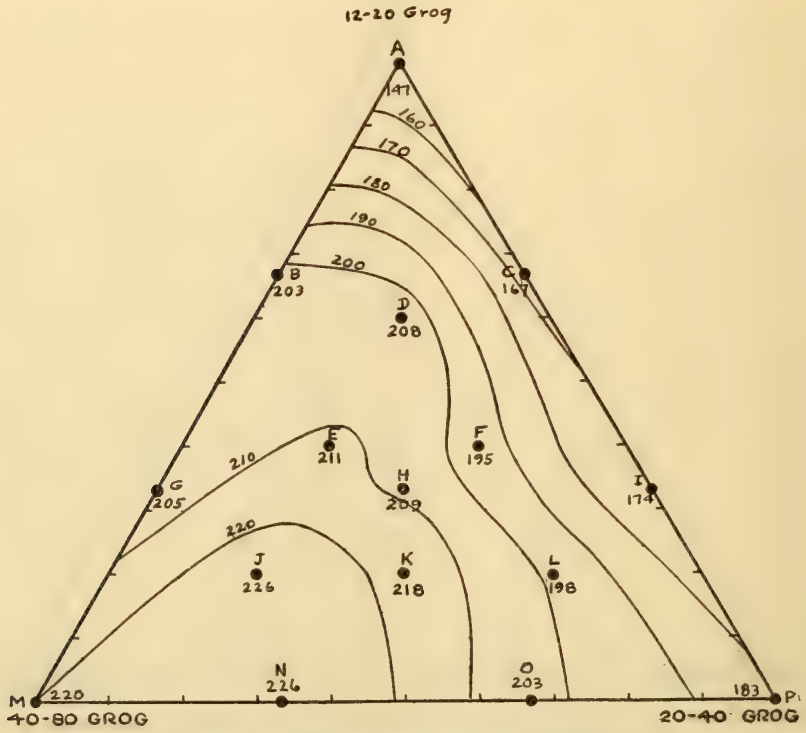

FIG. 10.—*Series 3. Relation between grog composition and modulus of rupture of raw bodies. Clay composition: All fire clay*

Fig. 15 shows the relation between the modulus of rupture and the size of grain, expressed as surface factor. If the iso-strength lines in the triaxial diagrams had run straight across the triangles, the relation would have been exact. Since they do not, an explanation of the results must be attempted by means of the theory of voids. It is obvious that mixtures of particles of different sizes give denser bodies than do single sizes, if they are related to each other so that the smaller sizes fit into the voids between the larger sizes. Since clay and grog have approximately the same specific

gravity, they occupy about the same volume per unit volume of briquette body. Hence, the grog particles are in contact with each other in the raw body, except for a comparatively thin layer of clay.

In Table 3 are given the average size of each grog portion and the ratio between the three average sizes in each series.

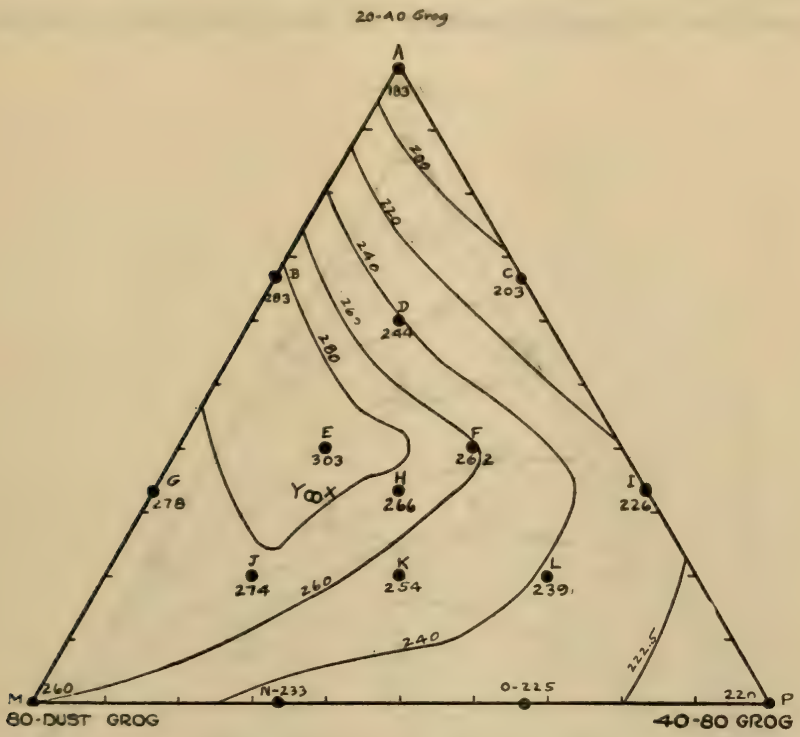

FIG. 11.—*Series 4. Relation between grog composition and modulus of rupture of raw bodies. Clay composition: All fire clay*

TABLE 3

Series	Mesh	Average size	Ratio of sizes	Series	Mesh	Average size	Ratio of sizes
		Inch				Inch	
1	4–8	0.1382	1.00	4	20–40	0.0214	1.00
	8–12	.0697	.50		40–80	.0101	.47
	12–20	.0423	.30		80–dust	.0032	.15
2	8–12	.0697	1.00	5–7	4–20	.0834	1.000
	12–20	.0423	.61		20–80	.0157	.188
	20–40	.0214	.31		80–dust	.0032	.038
3	12–20	.0423	1.00	Feret's sands[a]	4–10	.139	1.00
	20–40	.0214	.51		10–30	.050	.36
	40–80	.0101	.24		30–dust	.010	.07

[a] See Fig. 1.

If spheres of equal volume are packed symmetrically in a receptacle, two sizes of voids are formed between them and the three sizes of spheres necessary to form the densest mass have diameters in the ratio 1.00: 0.41:0.22. Since the actual shape and size of voids in clay-grog bodies can not be determined, the best means at hand for comparison of the effect of mixing different sized particles must be used. As the above table shows, the ratio of sizes in series 1 and 2 is such that the smaller particles do not fit into the voids, but

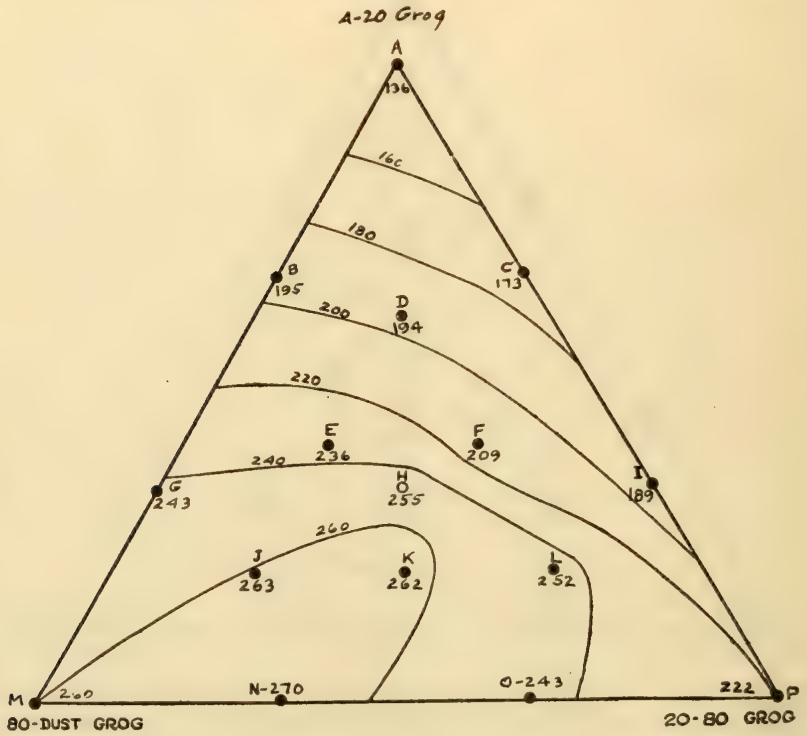

FIG. 12.—*Series 5. Relation between grog composition and modulus of rupture of raw bodies. Clay composition: All fire clay*

separate the larger particles. Hence, there are no maximum strength or density areas in these series. In series 3 there is a somewhat better ratio. The 40 to 80 size fits into the voids between either 12 to 20 or 20 to 40 mesh size, giving considerable increase in strength with amounts of 30 per cent and more and a maximum strength area near bodies *J* and *N*.

In series 4 the ratio approaches the theoretical ratio for spheres. The voids in the 20 to 40 material are able to contain 80 to dust material, but most of the 40 to 80 grog is too large, separating the

larger particles causing increase in porosity and decrease in strength.

In series 5 the ratio of sizes shows that the smaller sizes easily fit into the voids between the 4 to 20 size, giving some of the densest bodies obtained. These were not, however, the strongest. Most of the bodies in series 4 (20 to dust grog) were stronger than those in series 5 (4 to dust grog). The large particles in the latter weakened the bond and caused cracks in drying.

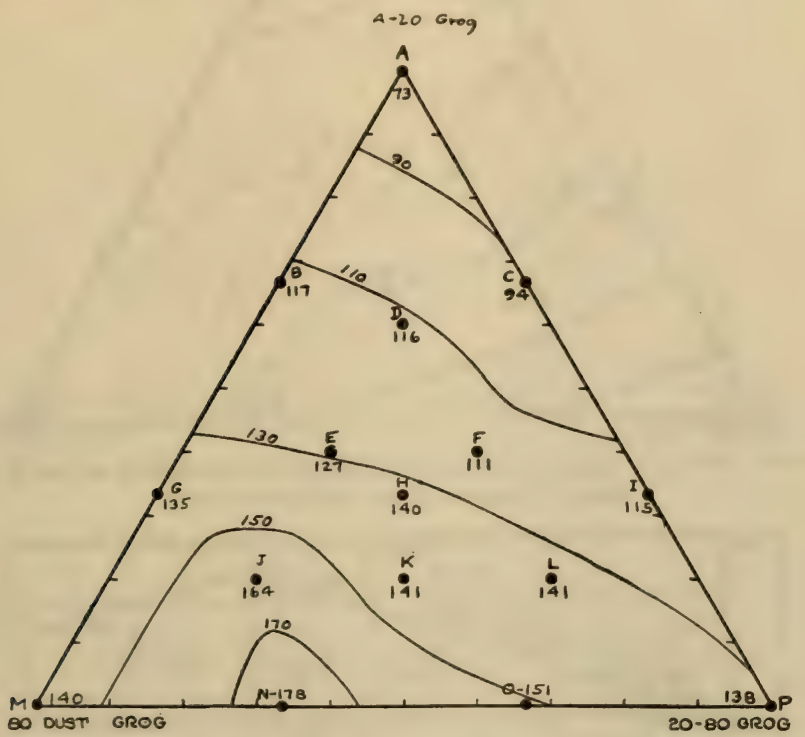

FIG. 13.—*Series 6. Relation between grog composition and modulus of rupture for raw bodies. Clay composition: Equal parts fire clay and Georgia kaolin*

The same ratio of grog sizes occurs in the bodies in series 6 and 7 as in series 5. The clay composition, however, is different in each of the three series. In series 6 the theory of the filling of voids applies as well as in series 5. The only difference to be noted is that the addition of Georgia kaolin decreased the strength to about 60 per cent of that of bodies in which the clay was all fire clay.

The results in series 7 were rather surprising when compared with those of series 5. The clays in both were plastic bond clays.

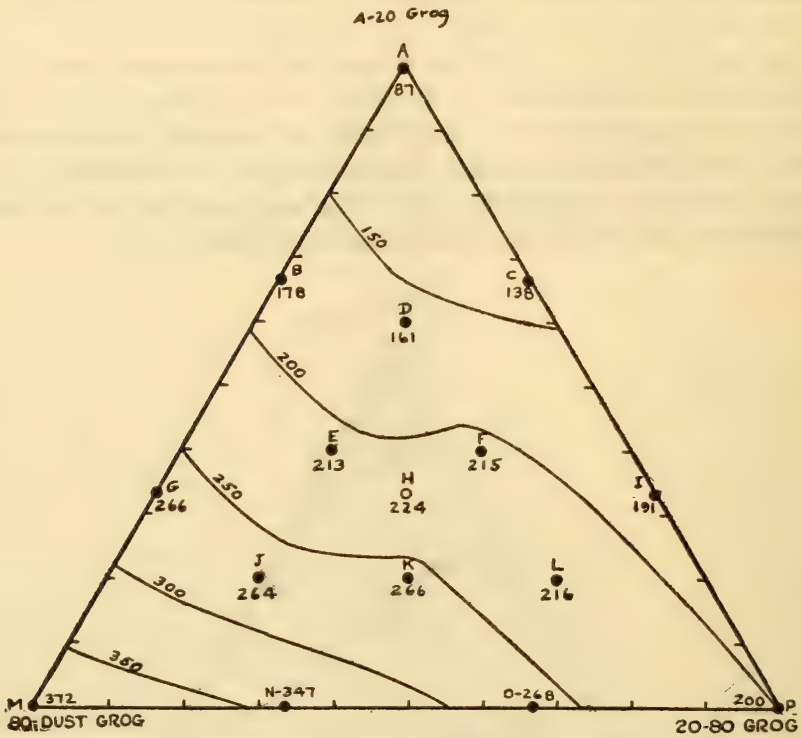

FIG. 14.—*Series 7. Relation between grog composition and modulus of rupture of raw bodies. Clay composition: All Illinois Kaolin*

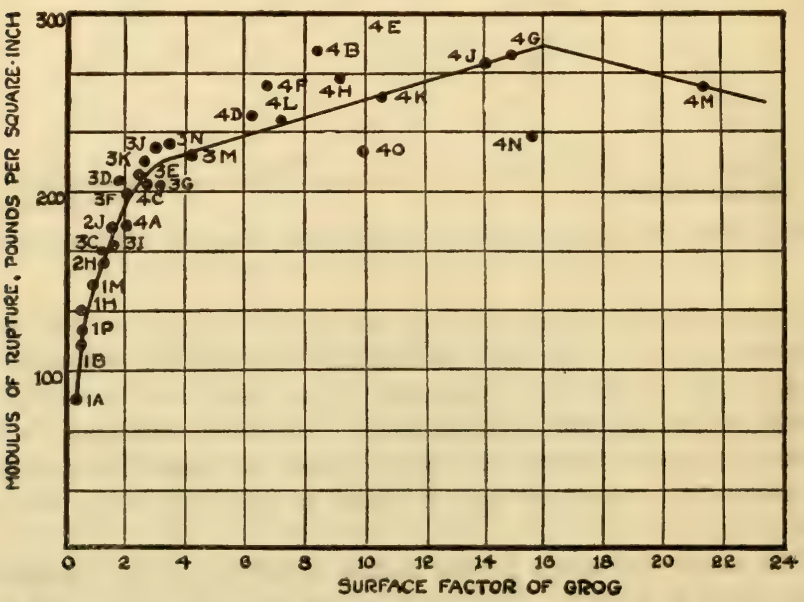

FIG. 15.—*Relation between surface factor and modulus of rupture of raw bodies*

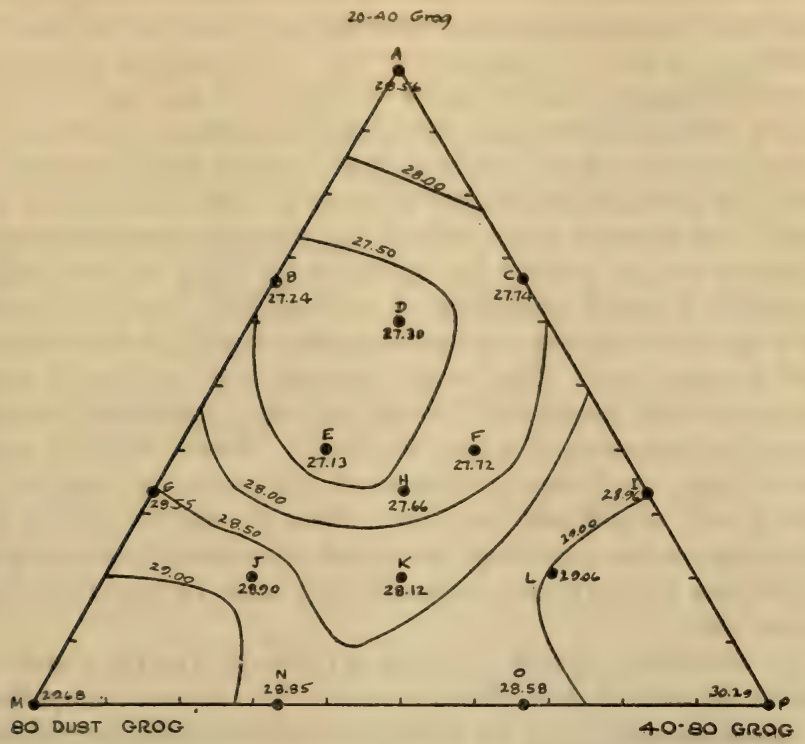

FIG. 16.—*Series 4. Relation between grog composition and porosity of raw bodies*

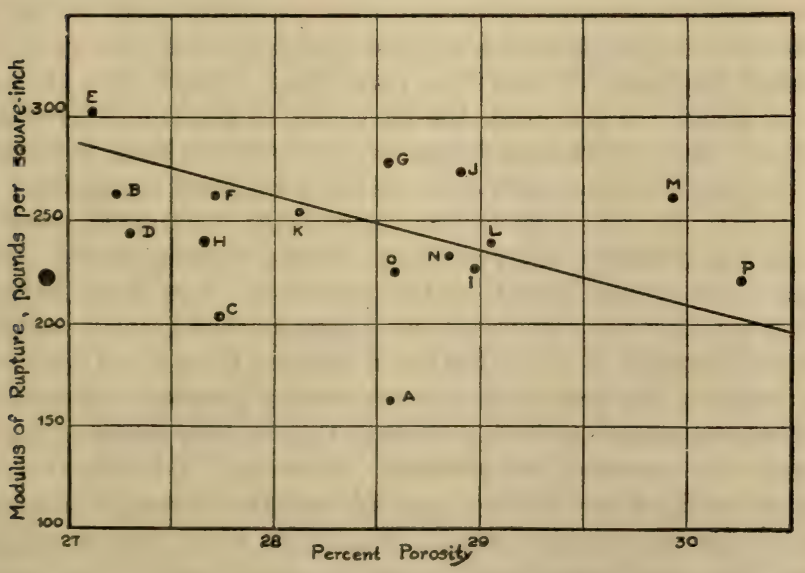

FIG. 17.—*Series 4. Relation between modulus of rupture and porosity of raw bodies*

The Illinois kaolin had less bonding power when coarse grog was used and more when fine grog was employed than had the fire clay. There are at least two reasons for this. The kaolin in the plastic condition is somewhat like putty, while the fire clay has more of a sticky nature and contains more colloidal material. If this were the only factor, all the bodies in series 7 should have been weaker than the corresponding bodies in series 5. But this was not the case. For example, body 7*M* had 1.43 times the strength of 6*M*. The only way to account for this is by assuming that the kaolin contained a certain proportion of grains of such size that they fit into the voids between the finer particles of grog, giving a denser and stronger body. This would indicate that the size of grain of the bond clay as well as the size of grog has considerable influence upon the properties of a fire-clay body. Hence, with the same size of grog, each clay or mixture of clays may be expected to give a body of different structure. Since the size of grain of the clays can not be accurately determined, the strength of clay-grog bodies can not be closely predicted, but must be ascertained by experiment.

(*c*) *Analysis of Results by Means of Granular Analysis Curves.*—While the ratio of sizes affords a convenient means of comparison it should be noted that the average size of each grog portion was used and that each contained particles varying in size from the maximum to the minimum. A more accurate method of study is offered by the granular-analysis curve as illustrated in Fig. 2. The curve of the strongest mixture is different for each group of similar mixtures. It may be a parabola, a straight line, or some other form. In any case, the curve shows accurately what the ratio of sizes shows approximately—that the mixture is so proportioned that the smaller sizes fill the voids most completely.

In Figs. 18 and 19 are shown analysis curves for series 4 and 5. Abscissas represent the percentage passing screens having openings of the sizes indicated by the ordinates. The lines denoted as "Parabola" are Fuller's curves of greatest strength and density. The clay portion of the bodies is not included since it is a constant. In series 4 the curves for bodies having greatest strength lie entirely between the full-line curves; that is, they follow approximately the course of the parabola. In series 5 it is seen that all the curves lie above Fuller's parabola and that strength decreases as the parabola is approached. For bodies which contain all the sizes, the maximum-strength curve is approximately that designated "maximum." With substitution of the proper values of

strength, Fig. 19 applies also to series 6 and likewise to series 7, except for the maximum curve. Thus, it is seen that the general

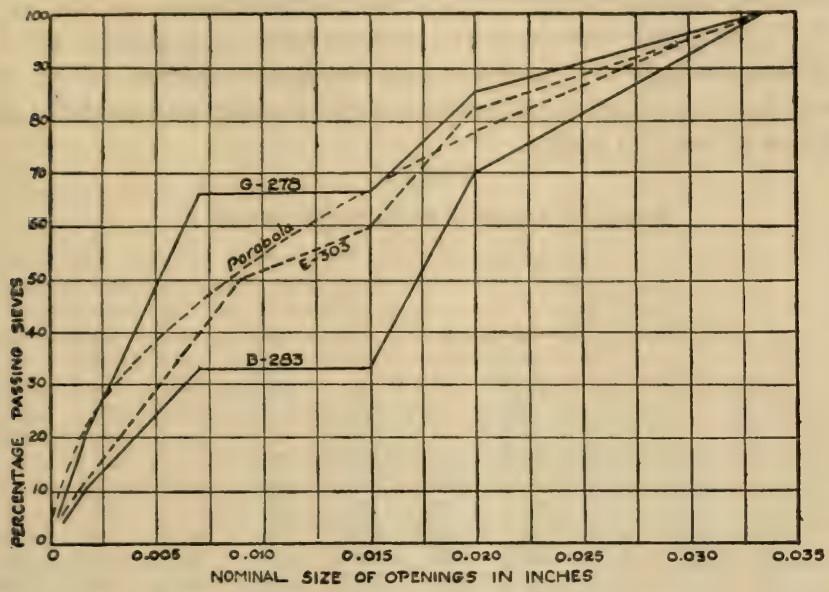

FIG. 18.—*Series 4. Mechanical analysis curves of grog*

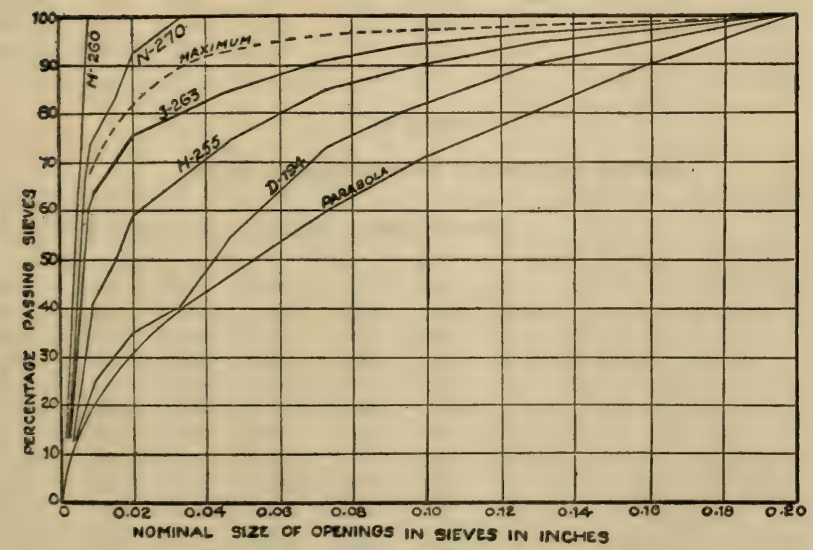

FIG. 19.—*Series 5. Mechanical analysis curves of grog*

principle of Fuller's law holds, although the law is not directly applicable in all cases.

2. RESULTS OF TESTS UPON BODIES IN THE BURNED STATE

(*a*) *Strength and Porosity.*—Bodies were burned to three temperatures, corresponding to heat treatments of cones 10, 12, and 14. Table 4 gives the moduli of rupture for cone 10 bodies, Table 5 shows strength, and Table 6 porosity of cone 12 bodies. Figs. 20 to 25 show the relation between grog composition and modulus of rupture of cone 14 bodies.

TABLE 4

Modulus of Rupture of Bodies Burned to Cone 10

	Series 1	Series 2	Series 3	Series 4	Series 5	Series 6	Series 7
A	390	698	919	1381	779	740	453
B	553	1141	1330	2294	1334	1232	1350
C	668	845	1014	1538	1061	1108	827
D	682	969	1394	1986	1302	1184	1121
E	780	1105	1491	2387	1687	1600	1658
F	563	923	1498	2251	1713	1619	1424
G	900	1328	1731	2618	1992	1835	1900
H	779	935	1673	2389	2011	1780	1869
I	731	941	1337	1555	1404	1384	1222
J	845	1298	1659	2160	2061	1972	2090
K	893	1205	1681	2011	2101	1904	1888
L	794	1037	1470	1875	1825	1737	1589
M	1029	1381	1978	2479	2479	2410	3012
N	1037	1188	1981	2368	2625	2484	2474
O	953	1100	1529	1976	2248	1973	1954
P	698	919	1381	1978	1700	1723	1429

TABLE 5

Modulus of Rupture of Bodies Burned to Cone 12

	Series 1	Series 2	Series 3	Series 4	Series 5	Series 6
A	529	716	925	1467	749	757
B	687	1000	1428	2400	1548	1395
C	549	742	1110	1628	1247	1039
D	589	935	1353	2074	1624	1402
E	660	1167	1623	2518	1954	1975
F	659	966	1439	2300	1861	1679
G	766	1218	1763	2815	2296	1919
H	749	1158	1859	2400	2158	2047
I	618	923	1300	1915	1656	1552
J	784	1219	1953	2683	2617	2512
K	684	1210	1823	2417	2632	2149
L	705	1100	1496	2208	2135	1847
M	925	1467	1866	3007	3007	2619
N	923	1300	1915	2808	3198	2859
O	742	1110	1628	2268	2744	2372
P	716	925	1467	1866	2200	1815

TABLE 6

Porosity of Bodies Burned to Cone 12

	Series 1	Series 2	Series 3	Series 4	Series 5	Series 6	Series 7
A	19.8	22.8	24.0	25.1	22.5	28.7	24.6
B	21.7	22.5	24.3	22.8	22.0	26.3	24.C
C	20.5	23.0	25.0	25.2	22.7	27.5	25.9
D	21.5	22.8	24.1	23.1	21.0	26.8	23.8
E	22.3	23.5	24.6	22.1	21.9	26.8	25.0
F	21.8	24.2	24.3	23.9	22.7	26.9	25.3
G	22.9	23.6	24.5	22.5	21.9	26.3	24.5
H	22.5	24.4	24.3	23.6	20.3	26.3	24.5
I	21.4	23.6	25.1	26.1	23.6	27.3	26.1
J	23.6	24.5	24.6	23.2	21.0	26.4	23.2
K	22.3	24.7	24.7	24.0	21.6	25.8	23.6
L	22.6	23.9	25.1	24.3	21.4	27.6	26.5
M	24.0	25.1	26.5	24.7	24.7	26.5	24.0
N	23.6	25.0	26.1	24.0	22.6	26.9	25.1
O	23.0	25.0	25.2	23.4	22.6	26.2	27.3
P	22.8	24.0	25.1	26.5	25.7	29.1	29.5

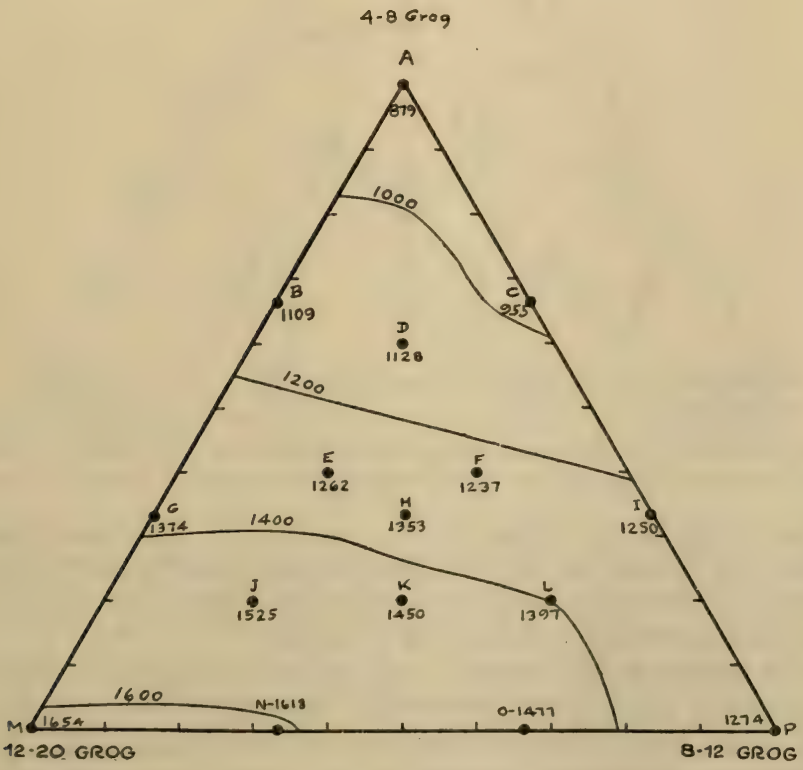

FIG. 20.—*Series 1. Relation between grog composition and modulus of rupture of bodies burned to cone 14*

In series 1 to 4 the modulus of rupture at cone 12 bears an approximate relation to porosity. The strength-porosity curve (Fig. 26) consists of two parts. From body 1*A* (4 to 8 grog) to bodies in series 3 (12 to 80 grog) strength increased with increase of porosity, due to small cracks which developed in drying and did not heal in burning. In series 4 (20 to dust grog) and part of series 3 strength decreased with increase of porosity, the degree of vitrifi-

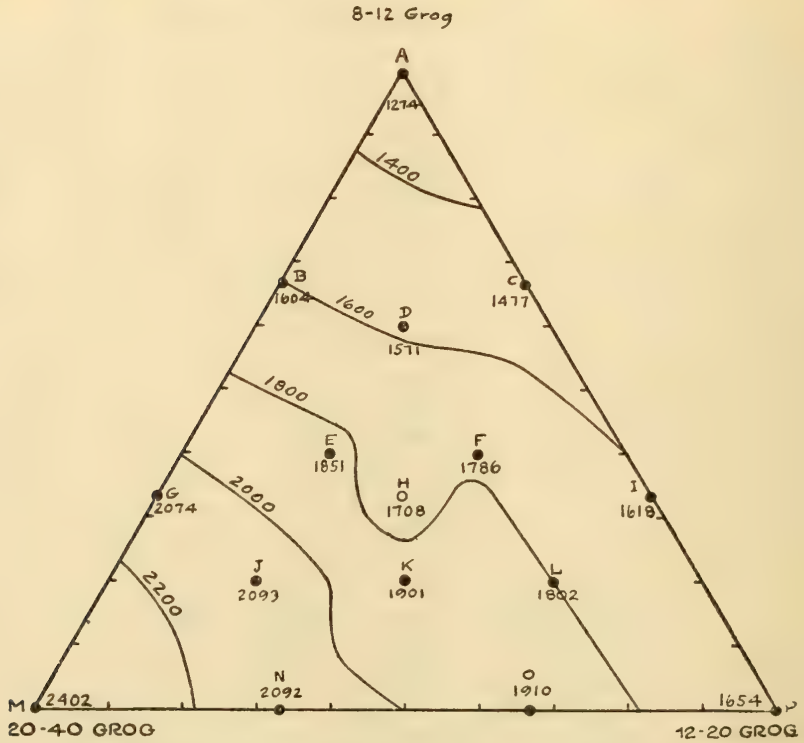

FIG. 21.—*Series 2. Relation between grog composition and modulus of rupture of bodies burned to cone 14*

cation being the governing factor. In series 5 (4 to dust grog) there was no relation between porosity and modulus of rupture. Hence, for bodies containing grog of different sizes, porosity may give entirely wrong indications of strength.

The surface factor, however, does afford an accurate means of judging the strength of such bodies. In Figs. 27 and 28 surface factor of the grog portion of the bodies is plotted against modulus of rupture. The curves are straight lines except that some are of

parabolic form in the lower part; that is, for larger grog sizes. The relation holds for all the series at all three heat treatments. It is more exact in series 1 to 4 than in series 5 to 7, because the latter contain comparatively large particles which are not dissolved by the clay to anywhere near the same extent as are the small particles.

(*b*) *Quenching Tests from 600° C.*—The results of these tests are presented in Table 7 and Fig. 29. Bodies retaining the greatest

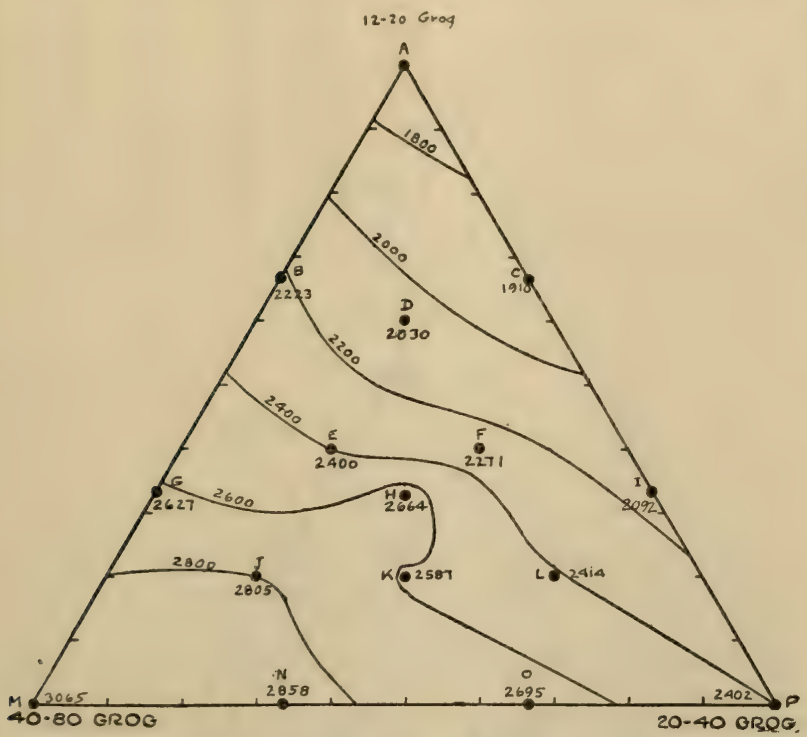

FIG. 22.—*Series 3. Relation between grog composition and modulus of rupture of bodies burned to cone 14*

percentage of strength were those in series 2, these, of course, overlapping certain portions of series 1 and 3. Bodies containing 8 to 40 mesh grog in the proper proportions withstood the treatment best, having values from 50 to 60 per cent strength retained. The bodies in series 5 and 6 nearly all retained a smaller percentage of strength than those in series 2, on account of the fine grog in the former.

TABLE 7

Per Cent of Strength Retained by Bodies after Quenching from 600° C Five Times

	Series 1	Series 2	Series 3	Series 4	Series 5	Series 6
A	34.2	46.3	50.0	53.4	46.6	43.4
B	48.5	54.8	42.5	39.6	40.8	48.2
C	38.8	50.4	50.6	48.4	51.7	50.7
D	40.6	51.2	48.7	36.4	47.9	51.6
E	43.9	47.3	45.9	37.8	42.4	43.4
F	48.5	49.5	47.0	36.9	43.0	48.1
G	46.5	49.2	39.7	32.4	30.5	32.7
H	46.6	54.5	41.4	36.8	49.2	40.4
I	41.4	50.0	48.0	41.8	49.4	57.1
J	50.1	57.6	38.0	37.5	27.5	27.5
K	55.0	53.2	42.5	37.2	35.2	35.0
L	58.3	50.0	46.9	36.6	46.4	50.2
M	50.0	53.4	40.0	14.3	14.3	18.7
N	50.2	48.0	41.8	31.4	18.5	18.4
O	50.4	50.6	48.4	37.8	34.0	31.0
P	46.3	50.0	53.4	40.0	55.3	48.0

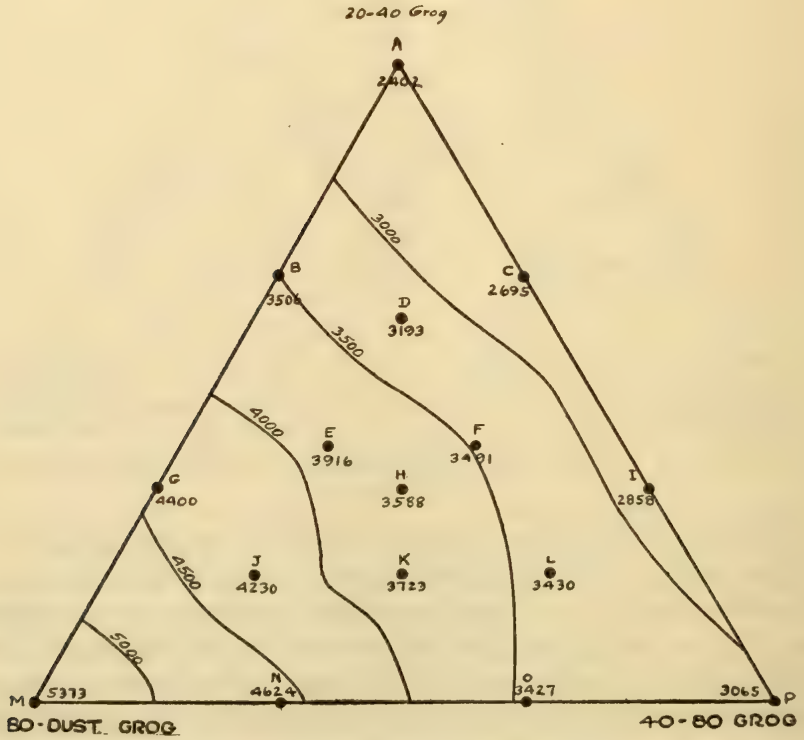

FIG. 23.—*Series 4. Relation between grog composition and modulus of rupture of bodies burned to cone 14*

(*c*) *Quenching Tests from 1000° C.*—The results from these tests are given in Table 8 and Fig. 29. The most resistant bodies were found in series 1 and 2 (4 to 40 mesh grog). In Fig. 29 surface factor is plotted against results of quenching tests. The results for 600° C agreed fairly well with those for 1000° C. Since this is true, it might be possible to replace the 1000° test by the more accurate 600° test. In general, increase of surface factor caused

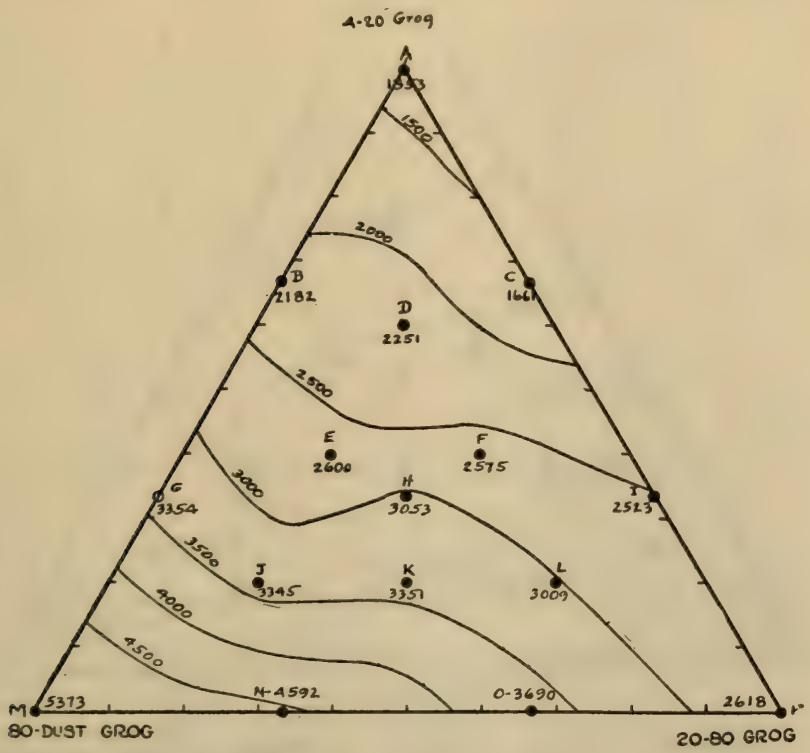

FIG. 24.—*Series 5. Relation between grog composition and modulus of rupture of bodies burned to cone 14*

decrease in resistance to sudden heating and cooling. The portion of the curve from 1*A* to 1*D*, etc., indicates that the largest size grog was too large for the briquettes used, causing spalling and destruction of the body. Four standard-size fire brick containing small-size grog (through 20 mesh or finer) were heated with the briquettes in these tests. The brick cracked in two on the average at the seventh treatment. Two fire brick containing large-size grog (about ¼ inch) cracked or spalled in two on the average upon

the twenty-fifth treatment. Hence, standard-size brick of the compositions used in this investigation would withstand, on account of their dimensions, two or three times the number of treatments undergone by the briquettes before breaking in two.

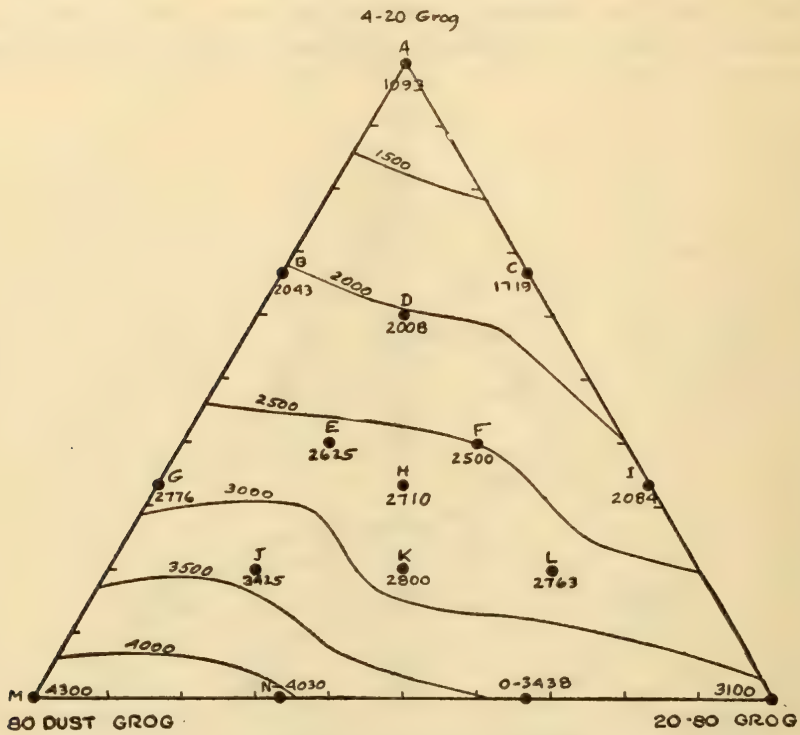

FIG. 25.—*Series 6. Relation between grog composition and modulus of rupture of bodies burned to cone 14*

(*d*) *Volume Shrinkage.*—Volume shrinkage of the bodies in burning to cone 12 is given in Table 9. Comparison of the values in Tables 6 and 9 shows that increase in shrinkage corresponds to decrease of porosity. Neither of these properties, however, corresponds to changes in strength. It is noted that shrinkage in series 7 was much greater than in any other series, due to the nature of the Illinois kaolin.

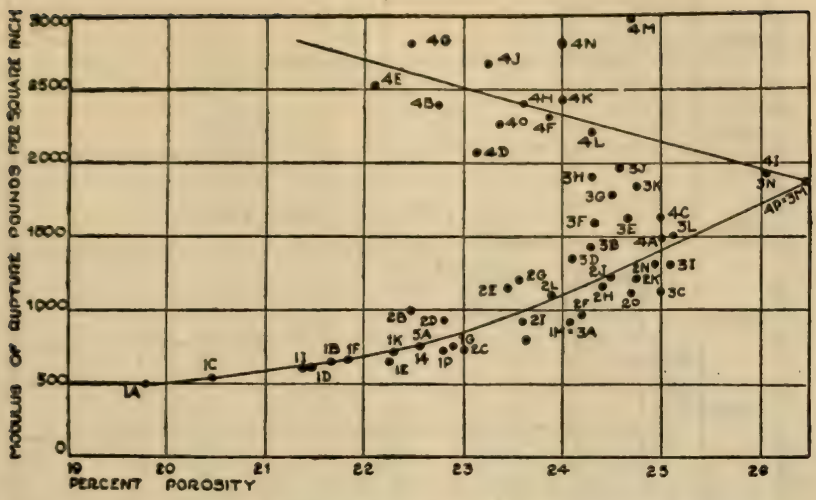

FIG. 26.—*Relation between porosity and modulus of rupture at cone 12*

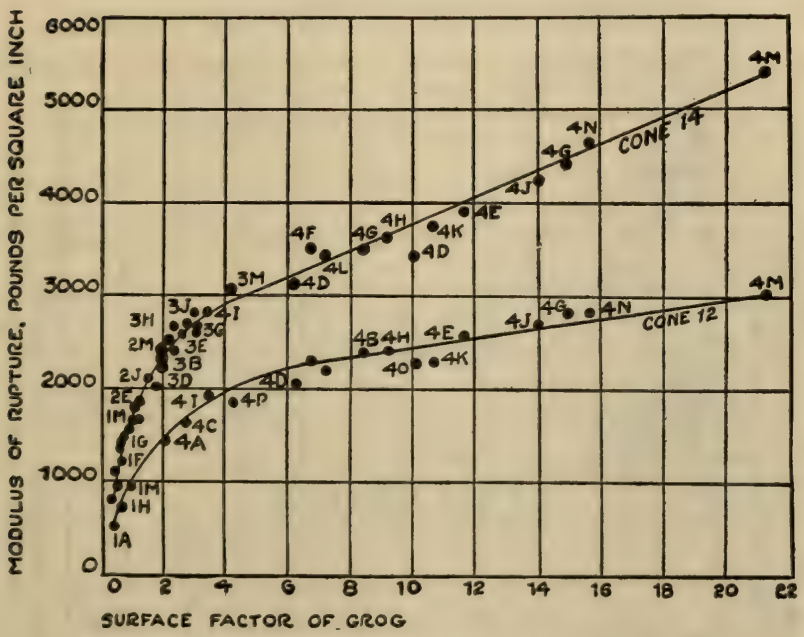

FIG. 27.—*Relation between surface factor and modulus of rupture*

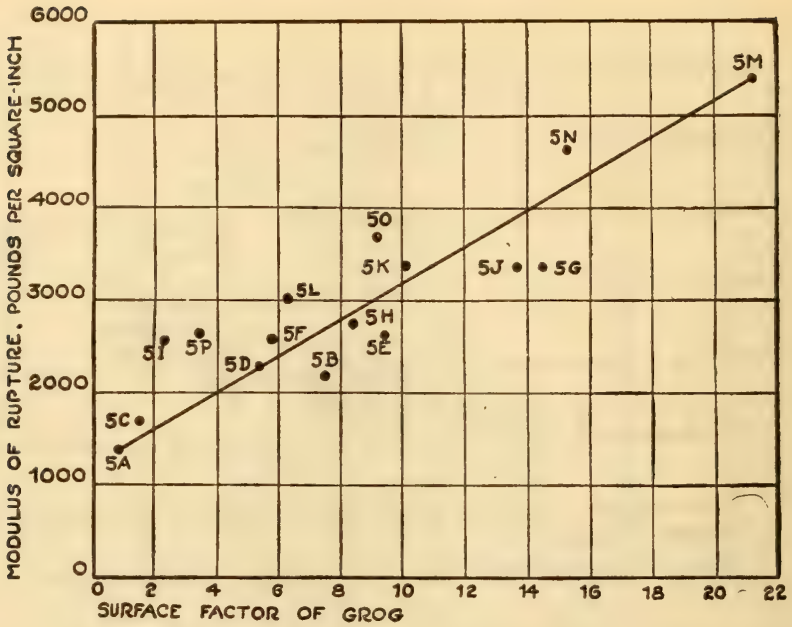

FIG. 28.—*Relation between surface factor and modulus of rupture*

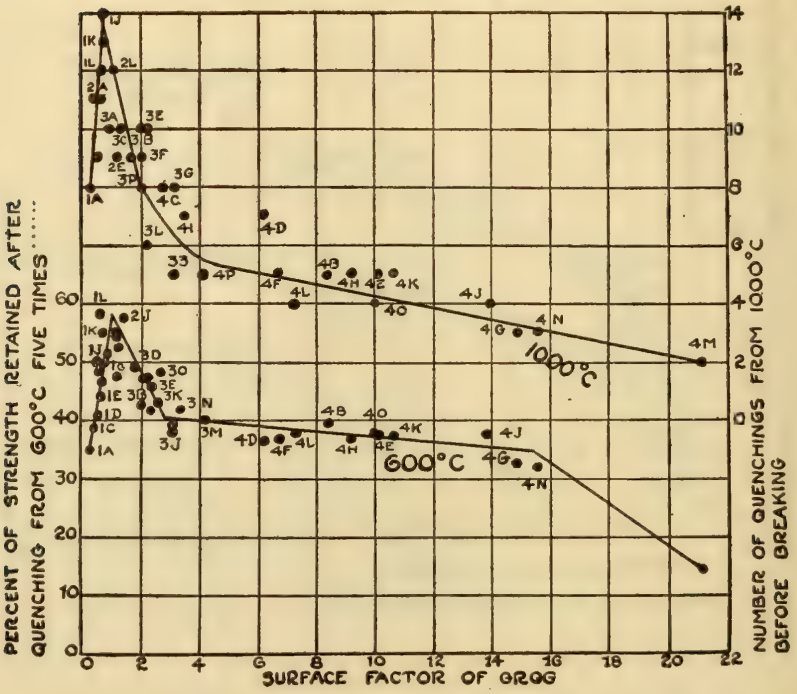
PERCENT OF STRENGTH RETAINED AFTER QUENCHING FROM 600°C FIVE TIMES
NUMBER OF QUENCHINGS FROM 1000°C BEFORE BREAKING
SURFACE FACTOR OF GROG
1000°C
600°C

FIG. 29.—*Relation between surface factor and results of quenching tests*

TABLE 8

Number of Quenching Treatments Withstood from Temperature of 1000° C

	Series 1	Series 2	Series 3	Series 4	Series 5	Series 6
A	8	11	10	8	12	3
B	9	10	10	5	4	5
C	11	10	10	8	5	8
D	12	10	9	7	3	7
E	12	9	10	5	3	6
F	12	11	9	5	3	6
G	10	8	8	3	2	2
H	12	11	10	5	2	3
I	11	10	9	7	3	5
J	14	9	4	4	2	1
K	13	10	4	5	2	2
L	12	12	6	4	3	5
M	10	8	5	2	2	1
N	10	9	7	3	2	3
O	10	10	8	4	2	3
P	11	10	8	5	3	4

TABLE 9

Volume Shrinkage of Bodies, in Per Cent of Burned Volume, Burned to Cone 12

	Series 1	Series 2	Series 3	Series 4	Series 5	Series 6	Series 7
A	8.55	8.03	7.53	7.75	6.96	9.15	9.40
B	5.85	6.57	6.41	9.24	7.28	8.28	13.51
C	9.06	7.38	6.52	7.40	5.64	8.47	14.66
D	7.48	7.70	6.53	8.24	7.50	8.72	13.84
E	7.19	7.45	6.66	10.67	8.08	8.75	13.58
F	7.85	7.46	7.45	7.57	6.80	7.67	13.72
G	7.00	7.37	7.93	9.72	8.68	9.00	13.30
H	6.96	7.21	7.36	8.40	9.23	9.86	12.49
I	6.90	7.50	6.45	6.81	6.52	9.35	12.20
J	4.81	6.79	7.02	8.27	10.35	9.76	14.18
K	7.21	7.09	7.63	9.57	8.41	10.66	13.68
L	6.53	6.34	7.93	8.35	9.86	10.33	12.85
M	7.53	7.75	8.15	9.94	9.94	9.74	14.14
N	7.50	7.10	8.40	9.40	9.68	9.75	13.42
O	7.38	5.89	7.50	9.78	8.95	9.61	12.98
P	8.03	7.53	7.75	8.15	7.35	8.27	11.78

TABLE 10

Surface Factor[a] of Grog Portions of Bodies

	Series 1	Series 2	Series 3	Series 4	Series 5–7
A	0.308	0.582	0.956	1.950	0.613
B	.525	1.038	2.037	8.409	7.530
C	.400	.707	1.286	2.703	1.430
D	.552	.930	1.805	6.241	5.254
E	.622	1.204	2.455	10.164	9.404
F	.547	1.000	2.000	6.729	5.744
G	.741	1.494	3.126	14.882	14.448
H	.616	1.163	2.371	9.169	8.348
I	.491	.832	1.615	3.443	2.248
J	.752	1.478	3.097	13.939	13.555
K	.677	1.278	2.654	10.610	9.895
L	.602	1.080	2.200	7.172	6.236
M	.956	1.950	4.211	21.365	21.365
N	.832	1.615	3.456	15.631	15.266
O	.707	1.286	2.702	9.991	9.166
P	.582	.956	1.947	4.190	3.066

[a] Calculated in the usual manner, the diameters of the particles being expressed in millimeters.

VI. SUMMARY OF RESULTS

The control of the strength of raw fire-clay bodies is a difficult matter into which enter a number of factors. Those which are directly connected with the size of grog are size of the body, cracks formed in drying, density or porosity, and size of grain of the clay.

If the grog is too large for the size of body used, the conditions of bond are different than for smaller grog. Small cracks may or may not form in drying. Hence, it is possible that the curve of Fig. 4 would be much different for test pieces of larger dimensions. The general rule in ceramic bodies is that strength increases with decrease of porosity. This factor may be overruled by others, as the results in Fig. 4 show. In series 4, however, the rule holds. As shown in connection with series 5 and 7 the size of grain of the bond clay also affects the strength of the body. In regard to the grog, aside from other considerations, the following condition is necessary for highest strength. The mixture of sizes must be such that the smaller particles fill the voids between the larger, giving maximum density. The proper proportions may be predicted qualitatively from the ratio of sizes, but can be determined accurately only by experiment.

The strongest raw bodies were those in series 4 and 7. In series 4 these had the following limits of grog composition: 25 to 66⅔ per cent, 20 to 40 grog; 0 to 25 per cent, 40 to 80 grog; and 33⅓

to 66⅔ per cent, 80 to dust grog. In series 7 the strongest bodies were those containing the greatest percentage of 80 to dust grog.

The control of strength in the burned state proved to be not at all difficult. For all bodies used the modulus of rupture was found to increase with increase of surface factor. The relation was represented by means of straight lines except that the lower portions of some of the curves representing large-sized grog were of parabolic form. The rate of increase of strength increased with the temperature of burning, due to the more rapid rate of solution of the finer particles at the higher temperatures. The porosity at cone 12 varied much the same as in the raw bodies and had little relation to strength. The strongest bodies were those in series 4 (20 to dust grog). No relation was found between strength in the raw state and in the burned state.

In the quenching tests from 600° C and 1000° C mixtures of the larger sizes of grog gave the more resistant bodies.

VII. APPLICATION OF RESULTS

Although the laboratory investigation has not been supplemented by practical work, it may be of value to indicate a few methods of application. Grog for glass pots and similar bodies may contain too much fine or intermediate-sized grog, causing low strength and cracking in drying. The composition of 20-mesh grog may be corrected by reference to Fig. 11. The best bodies have compositions within the maximum strength area described above. These had moduli of rupture of from 275 to 300 pounds per square inch in the raw state and from 3500 to 4400 pounds per square inch in the burned state. Point *X* in Fig. 11 represents the composition shown by the parabola of Fig. 18. Point *Y* represents closely the composition of grog furnished by the Harbison-Walker Refractories Co., of Pittsburgh, Pa., for the investigation of Bleininger and Schurecht on European Plastic Fire Clays.[7] This shows that grog may be ground to give the proportions for maximum strength. Where screening into separate sizes and recombining is not economical, this may be accomplished by control of the conditions of grinding, as time, size of openings in screen plates, pressure, etc.

The question of sagger loss is a serious one in many plants. A review of German, French, and American practice discloses many different methods of sagger manufacture. Composition is

[7] B. S. Technologic Paper No. 79, p. 19.

much varied. The clays used are of all grades from kaolins to shales and possess all degrees of plasticity and refractoriness, necessitating the use of various percentages of grog. The latter varies in composition from the best flint fire clay to used bats of various degrees of disintegration.

In American practice grog for saggers is used all through 3 to 6 mesh screens, while German and French manufacturers separate it into two or three sizes, classified roughly as fine, medium, and coarse. There is a wide variation in the proportions of sizes used, there being apparently no fundamental basis of reason for compounding the mixtures. In general, the larger the sagger the larger are the sizes of grog used. In some instances additions of sawdust, coal powder, quartz sand, alumina, or other materials are added to the mixture to increase porosity or refractoriness. Many ingenious methods have been devised for shaping, molding, and reinforcing saggers. Machine-made saggers are found to be more satisfactory than handmade. The temperature of burning varies much and has considerable influence upon the length of life of the sagger.

In attempting to apply the results of this investigation to saggers the size of grog must be assumed to be the governing factor. Otherwise the application might go far astray. Other factors having been eliminated the grog compositions given in Table 11 seem best suited for saggers having walls and bottoms 1 inch in thickness.

TABLE 11

		Per cent of composition passing sieves					Per cent strength retained, 600° C test	Quenching treatments withstood, 1000° C test	Modulus of rupture, pounds per square inch	
		4–8 mesh	8–12 mesh	12–20 mesh	20–40 mesh	40–80 mesh			Raw state	Burned state
Group I	1K	20	40	40	.....	.....	55.0	13	142	1450
	1L	20	60	20	.....	.....	58.3	12	136	1525
	2J	.....	20	20	60	.....	57.6	9	180	2093
	2H	.....	33⅓	33⅓	33⅓	.....	54.5	11	162	1901
Group II	3A	.....	.....	100	.....	.....	50.0	10	147	1654
	3C	.....	.....	66⅔	33⅓	.....	50.6	10	167	1910
	3D	.....	.....	60	20	20	48.7	9	208	2030
	3F	.....	.....	40	40	20	47.0	9	195	2271
	3I	.....	.....	33⅓	66⅔	.....	48.0	9	174	2092
	3L	.....	.....	20	60	20	46.9	6	198	2414
	3O	.....	.....	.....	66⅔	33⅓	48.4	8	203	2695
	3P	.....	.....	.....	100	.....	53.4	8	183	2402

Group I is recommended where resistance to repeated heating and cooling is desired more than strength. In Group II resistance to repeated heating is sacrificed to obtain bodies of greater strength. The results show that both very large and very fine grog are undesirable in sagger bodies of the compositions used in this investigation.

The results throw some light upon the question of the bonding power of plastic clays. The strength of clay-grog bodies in the raw state is a measure of bonding power. Since size of grog has great effect upon strength, size of grain of the clay must exert considerable influence upon this property. The size of grain of bond clays can not at present be measured accurately. Any means for determination or indirect estimation of this property, such as viscosity of the clay slip, would be of great help in working out this problem.

In conclusion, the writer desires to express his thanks to Prof. A. V. Bleininger, Prof. G. H. Brown, and H. G. Schurecht for their cooperation and assistance in the laboratory work and in the theoretical discussion of the results.

WASHINGTON, June 12, 1917.

DEPARTMENT OF COMMERCE
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S. W. STRATTON, Director

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COMPARATIVE TESTS OF PORCELAIN LABORATORY WARE

By C. E. Waters, Chemist

Porcelain is of but slightly less importance than glass in the chemical laboratory. In ordinary use it soon becomes evident whether or not the ware is mechanically strong and whether it is able to withstand sudden changes in temperature. In exact analytical work it is equally important that the glaze should offer the maximum resistance to attack by reagents. For many years chemists had at their disposal certain makes of ware which were of excellent quality, so that the resistance of porcelain to reagents was almost a laboratory byword. The placing on the market of ware from other sources and the inability to obtain the familiar brands made it desirable to subject both the new and old kinds to a series of comparative tests.

At the outset it was recognized that the results would probably not be as clear-cut and definite as those with glass. The weight of the porcelain prevented the testing of crucibles and dishes above a certain limited size. This meant that only a small surface of presumably highly resistant material would be exposed to attack. In addition, the shapes of the crucibles, and still more of the dishes, varied for the different makes, so that with a given volume of reagent not necessarily the same area of glaze would be attacked. During the progress of the work it was found that this factor was of slight importance, because the losses due to the action of the reagents were usually so small as to be negligible for most ana-

lytical work. After all it is desirable to know to what extent a given volume of solution may become contaminated, rather than how many square centimeters of porcelain it will wet.

BRANDS TESTED

At the time the tests were made only five makes of glazed porcelain ware could be obtained. In the laboratory stock the necessary number of Royal Berlin dishes, but no crucibles, was found. Meissen ware could not be obtained, but dishes and crucibles of "Bavarian" ware were purchased. In addition to these, a supply of a Japanese brand, marked "S. C. P.," and of two American makes, Herold (Coors) and Guernsey, were bought. All of the purchases were made in the open market.

The dishes were the largest that could be placed upon the balance pans. Nominally 80 mm in diameter, they varied from 78 to 95 mm for the different makes. The crucibles ranged in height from 35 to 50 mm, and in diameter from 57 to 65 mm. The different pieces of any one kind of ware were quite uniform in diameter and in general shape, but the variations in thickness were rather large. This was shown by the weights, which varied as follows: Herold (Coors), 34.5 to 43.1 g; Guernsey, 36.2 to 44.5 g; Bavarian, 34.1 to 43.0 g; Berlin, 29.4 to 37.3 g; Japanese, 32.3 to 43.0 g. The last-named ware showed the maximum variation, which amounted to 33 per cent. These figures are for 33 to 36 dishes of each kind of porcelain.

PREPARATION OF PIECES

Each piece was roughly weighed and, after having been arranged in the order of its weight, was lightly marked near the rim by means of a writing diamond. During the tests no breaks started at these diamond scratches. The lightest piece of each kind was used as a tare against which all weighings of that ware were made.

The pieces for the heating tests were not cleaned further than by wiping with a damp towel before the first rough weighing. The pieces used to test the action of reagents were rinsed with water, hydrochloric acid (1:1), and again with water, after which they were wiped dry on the outside. They were then kept filled with distilled water for 20 hours, rinsed, wiped dry, heated to 110° for two hours, cooled in the air, and weighed not sooner than three-fourths hour and usually much longer after their removal from the air bath. The tares were heated with the test pieces before each set of weighings.

SELECTION OF TEST METHODS

Suggestions as to the methods of testing and the reagents to use were received from various sources. No particular search of the literature was made, but it is believed that the fusions with sodium nitrate and the ignition with ferric oxide are new. The reasons for most of the tests are obvious, and for the others are given further on.

EXPERIMENTAL

All tests were made in duplicate, and the results are given in tabular form.

SUDDEN COOLING

Each piece was three-fifths filled with paraffin at 100° C, then brought to the desired temperature on a hot plate. It was then floated on water at room temperature. There were no failures on cooling from 200° C, but a number of dishes and crucibles cracked or broke when they were cooled from 225° C.

SUDDEN HEATING

The pieces were placed on a wire triangle and heated in the full flame of a Fletcher burner of the Méker type. After 3 minutes the flame was removed and 10 seconds later the piece was removed with platinum-tipped tongs. By this time the porcelain had cooled to a pale straw-yellow, at which temperature it would ordinarily be placed in a desiccator or otherwise handled with tongs. Quite unexpectedly this proved to be an important test, for in many cases the glaze cracked where touched by the tongs. When this happened after the first heating, new cracks were formed after one or more of the three succeeding heatings of 2 minutes each. In no case did the cracks first appear after one of these later heats.

The Royal Berlin and Japanese wares withstood this test satisfactorily.[1]

TREATMENT WITH SODIUM HYDROXIDE

After the usual preliminary cleansing, drying, and weighing, each piece was placed on the steam bath and then 50 cc of 10 per cent sodium-hydroxide solution was carefully poured in. The dishes did not rest in the openings of the bath but on thin plates of aluminum, in order to avoid the solvent action of directly im-

[1] Samples of Coors ware of recent manufacture have been found to withstand this test.

pinging steam. After five hours' heating, 30 cc of water was added to each dish to make up for that lost by evaporation. An hour later the pieces were rinsed out under the tap, dipped into hydrochloric acid (1:1), again washed, wiped dry, heated in the air bath, and finally weighed after cooling in the air. A second treatment exactly like the first was given.

The losses in weight found were greater than those caused by any other reagent, but the crucibles gave so much lower figures than the dishes that only the latter were used in the remaining solubility tests.

TREATMENT WITH SODIUM CARBONATE

The solution used contained 100 g of the anhydrous salt in 1,000 cc. The dishes were cleansed as for the preceding test. There were two treatments of seven hours each. The losses by evaporation were made up by adding 10-cc portions of distilled water at intervals of about two hours.

TREATMENT WITH SULPHURIC ACID

The cleansed and weighed dishes, each containing 25 cc of concentrated sulphuric acid, were heated on a hot plate for three hours at a temperature high enough to cause strong fuming. After washing out the acid and drying and weighing the dishes, it was noticed that one of them had a small crevice in the edge. Since this still contained acid, all the dishes were soaked in distilled water for three hours, rinsed, dried, and again weighed.

TREATMENT WITH FUSED SODIUM NITRATE

Since no oven suitable for use at temperatures above the melting point of sodium nitrate was available, the dishes were heated over burners. Thirty grams of the salt were placed in each dish and kept for two hours at such a temperature that there was a slight crust around the edges, while most of the nitrate was in the fused state. The melted salt was poured out and the cooled dishes were soaked for one and one-half hours in running water, then rinsed with dilute hydrochloric acid followed by distilled water. They were wiped dry, heated to 110° C, cooled, and weighed.

The losses in weight under this treatment were so unexpectedly small that a new series of tests was made with the same dishes at a higher temperature. The same weight of nitrate as before was slowly heated up to the point at which a piece of charcoal

floating on it caught fire. This required about 10 minutes. Under this treatment there were further losses, but the figures in the table, which show the combined losses during the two fusions, were still small.

TREATMENT WITH FUSED SODIUM-NITRATE-CARBONATE MIXTURE

A mixture of 10 parts of sodium nitrate and 1 part of carbonate readily fuses to a clear melt at a temperature higher than the melting point of the nitrate alone, yet still below a red heat. The action of even this strongly alkaline reagent was slight when 33 g of it was kept just at the melting point for two hours. After the usual cleansing and weighing the dishes were soaked in distilled water overnight. The very small changes in weight thus resulting are evidence against any considerable porosity of the porcelain. The figures in the table give the total losses during the three fusions.

The glaze at the bottom of some of the dishes was dulled, but did not appear to have been badly attacked.

IGNITION WITH FERRIC OXIDE

Ferric oxide so readily stains porcelain and is often so hard to remove as to suggest that it forms a silicate with the glaze. In this case the removal of the stain by prolonged digestion with hydrochloric acid might be expected to remove silica in soluble form, and possibly also other constituents of the altered glaze.

In order to coat the dishes as uniformly as possible with ferric oxide before ignition, the following procedure was adopted: To 20 cc of a solution of ferric nitrate (equivalent to 57 mg of Fe_2O_3) was added 5 cc of ammonia of half strength. The whole was evaporated to dryness, first on the steam bath and then in a radiator.[2] This was followed by gentle ignition over a small flame and finally five minutes' heating in the full flame of a Fletcher burner. After cooling, the dishes were wiped as clean as possible and weighed. Although all were badly stained, their increase in weight due to adhering ferric oxide was in no case as much as 1 mg. To each dish there was added 40 cc of hydrochloric acid (1:1) which removed the stains by digesting on the steam bath for three-fourths hour. The dishes were soaked in running water for one hour, then cleaned, dried, and weighed. The losses in weight were all very small and gave no evidence of the formation of any considerable amount of soluble silicates.

[2] Hillebrand, Bull. 422, U. S. Geol. Survey, p. 31, 1916.

POROSITY

The dishes that had been used in the nitrate fusions were soaked overnight in an aqueous solution of methyl violet, then rinsed quickly and wiped dry. All were strongly colored around the unglazed rim, and the numbers scratched on by the writing diamond stood out plainly. The spots where the glaze was dulled were faintly dyed. Nearly all of the color was removed by soaking for 20 hours in distilled water. In no case was there any evidence of pores or channels in the body of the material. The purple band around the edge was sharply limited by the glaze and showed no sign of creeping in under it. The dyeing effect seems to be due to adsorption by the rougher parts of the surface.

Results of Tests on Crucibles

Nature of test	Herold (Coors)		Guernsey		Bavarian		Japanese	
Heated to 200° C with paraffin and cooled suddenly in water	(a)	(a)	(a)	(a)	(a)	(a)	(a)	(a)
Heated to 225° with paraffin and cooled as above.	(b)	(c)	(c)	(b)	(c)	(c)	(b)	(b)
Suddenly heated in flame of Fletcher burner	(d)	(d)	(e)	(e)	(d)	(d)	(f)	(f)
Changes in weight in milligrams when—								
Heated with 10 per cent NaOH for 6 hours:								
First treatment	−1.8	− 1.9	−1.1	−1.6	−1.1	−1.6	−0.9	−0.7
Second treatment	−2.0	− 1.9	−1.7	−1.4	−1.2	−1.4	−0.7	+0.2

[a] The ware withstood this test satisfactorily.
[b] Did not crack.
[c] Cracked badly.
[d] Glaze cracked under tongs. Recent samples of Coors ware withstood this test.
[e] At third heat cracked badly at top and near bottom; glaze also cracked under tongs.
[f] No cracks in glaze.

Results of Tests on Dishes

Nature of test	Herold (Coors)		Guernsey		Bavarian		Royal Berlin		Japanese	
Heated to 200° C with paraffin and cooled suddenly in water	(a)	(a)	(a)	(a)	(a)	(a)	(a)	(a)	(a)	(a)
Heated to 125° C with paraffin and cooled as above	(b)	(c)	(c)	(c)	(c)	(c)	(c)	(c)	(c)	(c)
Suddenly heated in flame of Fletcher burner	(d)	(e)	(f)	(f)	(g)	(g)	(g)	(g)	(g)	(g)
Changes in weight in milligrams when—										
Heated with 10 per cent NaOH for 6 hours:										
First treatment	−2.3	−2.3	−2.6	−3.0	−2.5	−2.0	−1.4	−3.2	−1.0	−1.0
Second treatment	−2.6	−2.0	−2.5	−2.3	−2.4	−2.1	−0.6	−2.3	−1.2	−0.9
Heated with 10 per cent Na_2CO_3 for 7 hours:										
First treatment	−0.1	−0.1	+0.2	+0.1	−0.3	−0.3	−0.1	0.0	+0.3	+0.2
Second treatment	−0.3	−0.1	−0.8	−0.1	−0.3	−0.2	−0.1	−0.2	−0.3	−0.4
Heated with concentrated H_2SO_4:										
After washing	−0.1	0.0	−0.2	+0.1	0.0	−0.1	0.0	+0.1	0.0	0.0
After soaking (total)	−0.4	−0.4	−0.4	−0.3	−0.4	−0.5	+0.2	−0.3	−0.3	−0.4
Heated with fused $NaNO_3$ for 2 hours	0.0	+0.3	+0.1	0.0	+0.2	+0.2	+0.2	+0.2	+0.1	+0.1
Heated with $NaNO_3$ to ignition point of charcoal [h]	−0.5	−0.3	−0.5	−0.5	−0.3	−0.3	−0.5	−0.6	−0.6	−0.4
Heated with $NaNO_3$—Na_2CO_3 mixture for 2 hours: [h]										
After washing	−0.4	−0.3	−0.5	−0.7	−0.7	−0.6	−0.2	−0.5	−0.6	−1.3
After soaking	−0.5	−0.3	−0.5	−0.5	−0.4	−0.4	−0.3	−0.6	−0.5	−1.2
Ignited with Fe_2O_3:										
Before HCl digestion	+0.5	+0.3	+0.5	+0.2	+0.6	+0.5	+0.4	+0.3	+0.3	+0.4
After HCl digestion	−0.1	−0.2	−0.1	−0.2	−0.1	0.0	0.0	0.0	−0.2	−0.1

[a] The ware withstood this test satisfactorily.
[b] Broke.
[c] Withstood this test without breakage.
[d] Cracked all around on first heat. Recent samples withstood this test.
[e] Fell into two pieces on first heat. Recent samples withstood this test.
[f] Glaze cracked under tongs on first heat.
[g] No cracks developed.
[h] These figures represent the total changes in weight after two or three fusions, respectively, with sodium nitrate.

CONCLUSIONS

In general there is little choice between the five brands of porcelain tested as far as their resistance to reagents is concerned. One exception is their behavior with caustic-soda solution, in which test the Royal Berlin and Japanese wares were the best, if we except the apparently abnormally high result obtained with one of the Berlin dishes.

The two American wares and the Bavarian crucibles made a comparatively poor showing when suddenly heated or cooled. In both of these tests the Japanese and the Royal Berlin porcelain and the Bavarian dishes were equally good. No Berlin crucibles were available.

A serious defect of the American[3] and Bavarian porcelains was the cracking of the glaze when a hot vessel was picked up with tongs.

WASHINGTON, May 18, 1917.

[3] See footnote 1, p. 3.

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DEPARTMENT OF COMMERCE

TECHNOLOGIC PAPERS

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S. W. STRATTON, DIRECTOR

No. 106

STABILIZED-PLATFORM WEIGHING SCALE OF NOVEL DESIGN

BY

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I. INTRODUCTION

This paper treats of the theory and design of a new type of check-stabilized weighing scale, in which the usual pin-and-link stabilizing element is replaced by a flexible elastic tape or wire, a design which eliminates practically all the friction inherent in earlier stabilizing mechanisms, with the result that the total frictional resistance of the scale is sensibly independent of the position of the load on the platform.

[1] The author has been granted letters patent No. 1 218 092, under date of Mar. 13, 1917, on the type of weighing scale which forms the subject of this paper. A copy of that patent is given as an Appendix. It is to be noted that the invention therein described and claimed has been dedicated for the free use of the Government of the United States, or any person in the United States, without payment of royalties, as is usual in the case of patents granted on inventions within the field of work of staff members of scientific bureaus under the Government. This paper was submitted as a thesis in partial fulfillment of the requirements for the degree of Mechanical Engineer, at the University of Illinois, June, 1917.

By this expedient, which insures through suitable disposition of the platform, that the stress in the stabilizing element continues constantly in the sense of tension—the function of a stabilizing link being then satisfactorily and sufficiently fulfilled by a flexible connector—the utility and application of the check-stabilized scale are greatly broadened and the accuracy of the device is much increased.

The earlier types of stabilizing elements are illustrated and the limitations of each set forth. The equilibrium conditions of the platform and stabilizing element are derived, and the methods to be used in adjusting the scale are outlined. The paper includes a discussion of the effects of static friction on the indications of scales and shows how the elimination of this friction enhances the accuracy of weighings.

II. FUNDAMENTALS OF DESIGN OF STABILIZED SCALES

1. TYPE OF WEIGHING SCALES

For the purposes of this paper, weighing scales may be grouped into two broad classes—those having suspended platforms or weighbridges and those having stabilized platforms. In the first of these two classes is found the suspended-pan balance, familiar in the equal-arm balance used in analytical and scientific work; in the second class appear most of the weighing scales used in industry and commerce, where a suspended platform or weighbridge would be inconvenient and cumbersome. This inconvenience arises principally from two sources. In the first place, the suspended platform involves the use of chains or rods by which to hang the weighbridge from the weighing system; these rods limit the shape and dimensions of the load to be applied, and tend generally to interfere with the convenient and easy handling of the load. In the second place, the suspended platform acts as a pendulum, tending to swing about its point of suspension, due to the restoring moment which is introduced when its center of gravity is displaced from the vertical line containing the center of suspension.

The effect of this harmonic motion of the platform is to interfere with the reading of the indications of the scale, since these oscillations of the platform and its superposed load are communicated to the lever system and added to the natural oscillation of the weighbeam or pointer, causing an irregular distortion of the normal sine-wave vibration of the weighbeam. The effect of this distortion

is to obscure the estimation of the rest point or plane of balance of the scale.

On this account, in the use of a suspended-pan balance, it is essential to damp out by hand the swinging of the pans, so that the vibration of the pointer can be accurately observed, and read without the error which would result from the inclusion of the attendant vibrations of the platform. The necessity of thus damping the motion of the pans would cause much inconvenience, so that this type of scale is very little used industrially, in spite of its simplicity, accuracy, and reliability, and has been largely replaced by the various forms of stabilized-platform scales in practically all applications except those requiring the highest precision. This latter type of scale is very common; examples in great number are found in the so-called platform scales, in letter balances, wagon and track scales, etc., so widely employed, in all of which the weighing platform commonly lies above the plane of the lever system.

2. STABILIZING MECHANISMS

Two principal arrangements for stabilizing the platform have been commonly employed. The term "stabilizing" is used to denote the constraining of the platform to motion in a properly defined path, independently of the position of the load upon such platform. The first type of stabilizing mechanism is shown in Fig. 1, which illustrates the weighing mechanism of the four-point-support type, this mechanism being a very common one for scales of moderate and large capacity.

It will be seen that the platform is supported on two pairs of pivots or knife-edges, each of the triangles below the platform feet representing one pair of collinear knife-edges. As the platform bearings are held in contact with these pivots by the weight of the platform and the load it carries, the two pairs of bearings must assume the motion of the corresponding pairs of pivots. In this manner the motion of the platform is determined at all phases of its vibration, and the platform is therefore stabilized.

Now, it will be noted that this type of scale requires four pivots (or two pairs of collinear pivots) to support the platform, and in order that the motion of the platform proceed always into planes parallel to any assumed initial position (which is the necessary criterion for accuracy of weighing independent of the position of the load on the platform), the lever arms of which these knife-

edges form the pivots must be accurately adjusted to equality with each other.

Such adjustment being somewhat difficult and too expensive to permit the making of this type of scale at the low cost needful for scales of small and moderate capacity in some applications, another type of stabilizing element has long been used, in which the platform is carried on but one knife-edge, or one pair of collinear knife-edges, the parallel motion of the platform being provided for by a linkwork so adjusted that every part of the plat-

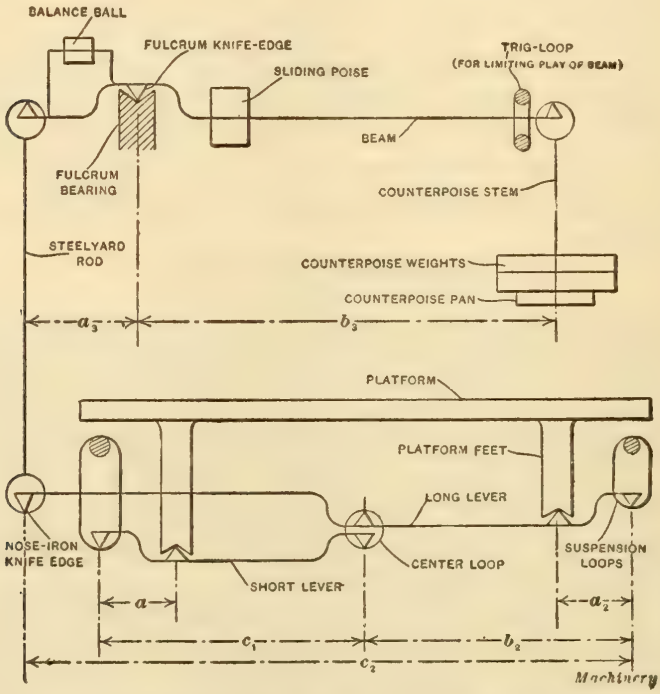

FIG. 1.—*Common form of platform scale, the platform of which is stabilized by being supported at four points in a plane*

Reproduced from the author's paper, "Weighing scales," in Machinery, January, 1916.

form describes, when oscillated through a small excursion, identically the same vertical displacement. This is equivalent to a statement that the linkwork is so designed as to resist only horizontal forces arising from noncentral placement of the load, or unsymmetrical weight distribution in the platform itself, all vertical components of forces due to the weight of the load being transferred, unchanged in amount, to the weighing mechanism of the scale.

3. FORCE RELATIONS IN THE CHECK-STABILIZED SCALE

Fig. 2 illustrates the construction of a scale having the properties set forth above. From this it may be seen that the total vertical component of the load on the platform and the weight of the platform itself is supported on the load knife-edge, the lower bar 2 of the linkwork assuming only the horizontal component which appears when the center of gravity of the platform load and of the platform itself, combined, lies outside the vertical plane containing the axis of the load knife-edge.

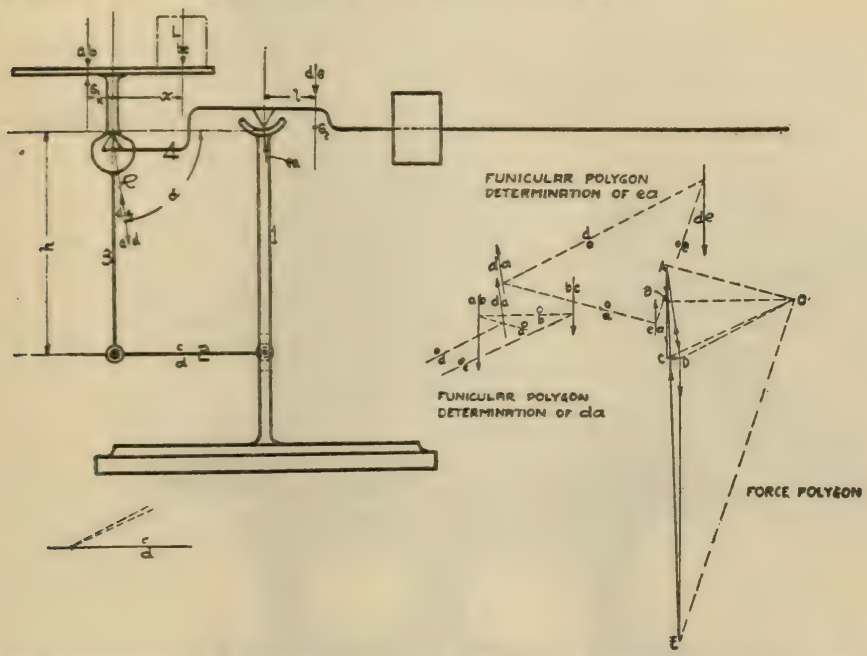

FIG. 2.—*Ordinary check-stabilized postal scale, having the pin-and-link type of check rod*

The force diagram at the right gives the solution for the stress in the check rod, and for the reactions at the load and fulcrum knife-edges.

It is to be noted here that, as actually constructed, scales of this type are usually characterized by compactness, portability, ruggedness, and durability, while their manufacture is not expensive and their adjustment is easily performed and not easily deranged.

However, a study of the mechanics of the scale, and experience in its use, leads directly to a knowledge of certain serious defects, and it was in the experimental investigation and analysis of these defects that the present invention, which forms the subject of this paper, was evolved. The nature and causes of the difficul-

ties, to which allusion is made above, are shown analytically in the following derivation:

The dotted lines in Fig. 2 show a load the weight of which is equal to L, its center of gravity being located at a distance x from the vertical through the load knife-edge (*3*, *4*). Given the nomenclature of Fig. 2, and calling T the stress in the link *2*, we obtain, by summation of moments, about (*3*, *4*)—

$$\Sigma M = Lx - G_1k - Th = 0$$

$$T = \frac{Lx - G_1k.}{h} \qquad (1)$$

Let R_x and R_y be the components of the reaction R at (*3*, *4*) in the X and Y directions, respectively.

By summation of forces in the X and Y directions, we obtain—

$$\Sigma F_y = -L - G_1 + R_y = 0, \text{ or } R_y = L + G_1 \qquad (2)$$

$$\Sigma F_x = -R_x + T \qquad \text{or } R_x = T \qquad (3)$$

$$\tan \alpha = \frac{R_y}{R_x} = \frac{L + G_1.}{T} \qquad (4)$$

Substituting the value of T from (*1*) in (*4*), we obtain—

$$\tan \alpha = \frac{(L + G_1)h}{L_x - G_1k} \qquad (5)$$

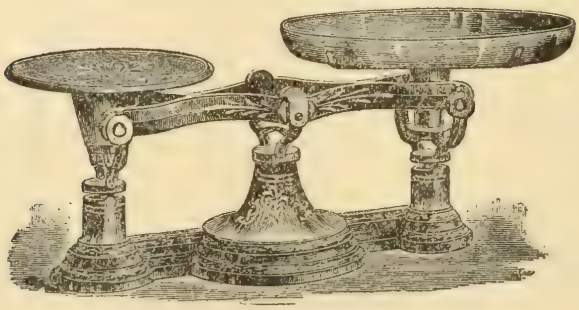

FIG. 5.—*Check-stabilized, equal-arm beam scale*

With this type, loose weights are required, in amount equal to the weighing capacity. Being inexpensive and, on account of simple construction, long wearing and reliable, it has been much used in small business of every sort. When the loads are carefully centered on the pans, the scale will weigh with very satisfactory accuracy.

To all of the familiar commercial forms illustrated in Figs. 3, 4, and 5, the invention which forms the subject of this paper is directly applicable.

This solution is given graphically in Fig. 2, and the force diagram is there extended to include also a solution for the reaction at the fulcrum pivot. As is shown by the above derivation, in all cases in which the resultant of the weights of the platform

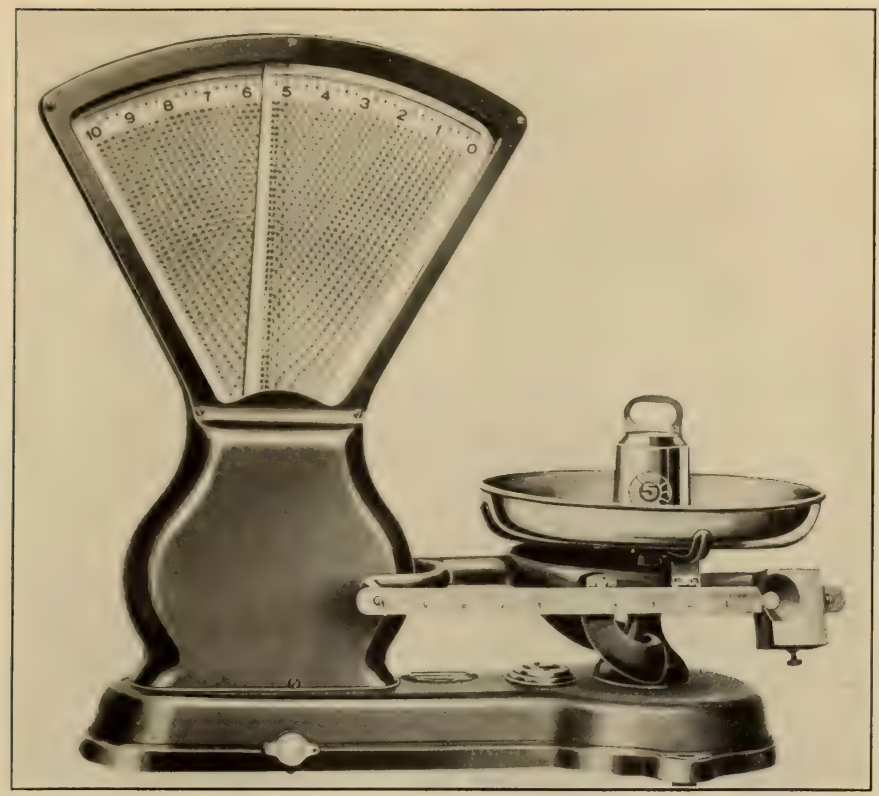

FIG. 3.—*Check-stabilized computing scale of a sort in common use in retail trade*

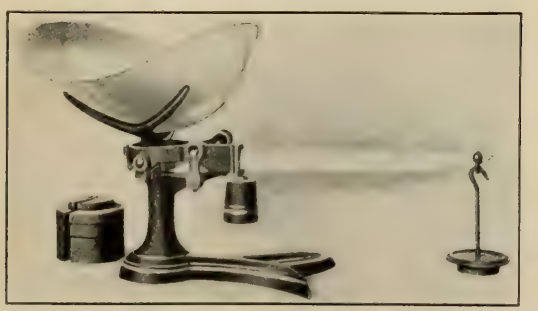

FIG. 4.—*Check-stabilized, unequal-arm beam scale (nonautomatic)*

This convenient and compact type of scale is much used in the hardware trade and in similar lines of business

and the superimposed load does not lie in the plane of the load knife-edge, a stress is introduced into the link *2*, which is called the stabilizing link, stabilizing check, or check rod, this stress being longitudinal, and in magnitude varying directly as the distance of the combined center of gravity of the load and platform from the vertical plane containing the load pivot, and, inversely, as the length of the link *3*.

Now, this introduction of a stress in the bar *2*, with the appearance of reactions at the journals (*1*, *2*) and (*2*, *3*), involves frictional resistance to turning at those journals. It is a fact that in check-stabilized scales as commonly constructed, this friction is detrimentally large in amount, resulting from the necessity of making the platform dimension in the X direction reasonably large, and of keeping the length of the bars *1* and *3* of the linkwork rather short, in order that compactness be not sacrificed.

4. DYNAMICAL CONSIDERATIONS

The motion of a vibrating scale beam is given by an equation of the form—

$$\theta = Ae^{-at} \sin \omega t, \qquad (6)$$

in which θ is the angular amplitude of the vibration at any phase; t, the time; ω, the angular velocity; and A and a are constants.

This equation is derived under the assumption of frictional resistance proportional to the first power of the velocity, an assumption which the writer's experiments have shown to be reasonably accurate for a weighing scale at moderate and large amplitudes of oscillation, where the preponderating portion of the damping is that due to the fluid friction of the medium (air) in which the scale parts oscillate. At very small amplitudes the air resistance becomes small in comparison with the inelastic resisttances of deformation of the knife-edges and bearings, and the wave form deviates in an irregular manner from that above defined, owing to a distinct change in the type of friction.

It may be stated as a general principle that in any weighing scale all frictional resistances which do not vanish at zero velocity of the moving parts are disadvantageous and productive of error, in that they cause uncertainty or variability in the readings of the apparatus. Fig. 7, which is an actual time curve of the excursions of a vibrating scale beam, indicates the cause of these errors. It will be seen that the final rest point is subject to variation, depending upon the amplitude of the initial excursion and the

direction or sense in which that excursion is made. The curves of Figs. 7 and 8 are reproduced from actual oscillograms taken by photographic means on a scale of the type illustrated in Fig. 2.

We may neglect for the present the effect produced by varying the position of the load upon the platform and the concomitant effect of such variation upon the absolute value of the frictional resistance at any given phase. It will be readily understood without special illustration here that for a given magnitude and sense of the initial excursion such change of load position alone would alter the final rest point.

(*a*) MEANS OF DETERMINING REST POINT.—A weighing scale may have its indications read in one of three ways. If the damping is slight, as in the case of precision balances, the position of the rest point is closely approximated by taking the mean of two, three, or more excursions of the pointer over a graduated scale or arc; or second, by waiting for the balance to come to rest, reading then the final position of the pointer; or third, by damping the balance artificially so as to make it approximately dead beat. It can easily be shown that none of these methods can give accurate results on a balance which has any appreciable static friction.

If the first method be used, the mean of three excursions will lie to one side or the other of the virtual rest point, according to the direction in which the first recorded swing was made. Similarly, if the second method be used, the rest point of the balance will not be definite, but will depend upon the total number of excursions it has executed before coming to rest, and if the balance is read in this way, every slight difference in the manner in which the balance is set in motion will result in a different rest point. In the third method, when the balance has static friction, the rest point will lie invariably on a determined side of the true point of balance, depending upon the direction in which the one excursion has been made; in other words, the excursion, no matter from which direction executed, will be consistently too short, and the final reading will be in error either in excess or deficiency, according as the reading has been taken at decreasing or increasing load.

We have seen, then, that in no case can a balance which has static friction give correct readings of the rest point. No proof is needed to show that upon the determination of the true rest point the accuracy of all weighing depends. In the ordinary platform scale we adjust by trial the equilibrating forces until the end of the beam plays, as closely as can be judged, in the center

FIG. 6.—*Curve of damped oscillations, reproduced from photographically recorded oscillogram*

This is a vibration of the form,

$\theta = Ae^{-at} \sin \omega t$.

The horizontal axis is that of time, while the vertical axis is that of angular displacements from the initial plane of balance. The value $\frac{\theta_1}{\theta_2}$ gives a measure of the amount of the damping. The values of the load corresponding to each oscillogram are recorded in each case. For example, in the curves of this figure, *a* is the oscillation for the scale with a load of 2.000 pounds, the distance *x* from the vertical plane through the load knife-edge being 4.7 inches. In *b*, an increment of 0.002 pound has been added, and in *c*, an additional 0.002 pound. At *d* both increments have been removed together, and at *e* both have been readded, together. Note the accuracy with which the axes of *a* and *d*, and of *c* and *e*, are collinear, respectively. The curves of this figure are taken from a scale having the type of stabilizing link presented for the first time in this paper.

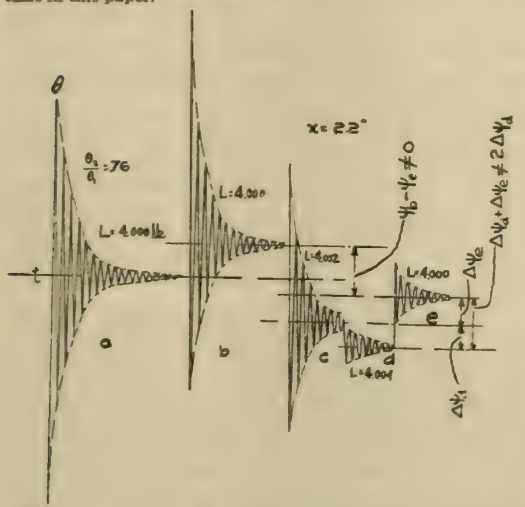

FIG. 7.—*Curves taken in a manner similar to those in Fig. 6, but on the old type of scale, having the pin-and-link check rod*

Curves *a* and *b* are for identical conditions, the scale simply being allowed to come to rest at the end of *a* and restarted for *b*. Note the variability of rest point here exhibited, and expressed analytically in the equations accompanying the figures.

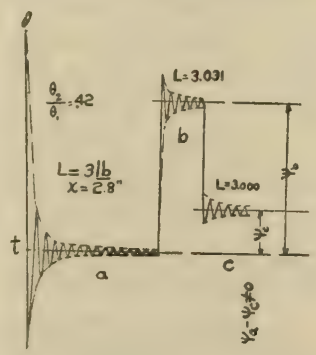

FIG. 8.—*Scale of same type as Fig. 7, but a different specimen*

The capacity of this scale is 20 pounds, and yet a large damping and variability occur with a load of only 3 pounds, displaced but 2.8 inches from the platform center, which lies in the the vertical plane through the load knife-edge.

These figures illustrate clearly the conception of "uncertainty of indication," discussed in the text.

of the trig loop. (See Fig. 1.) In another group of scales, similar to that illustrated in Fig. 2, the reading of the balance is made with reference to an estimated horizontal plane, the arc of oscillation of the beam being purposely made rather large so that deviations from the horizontal plane can be observed and varied by suitable alteration of the load or counterpoise weights.

(*b*) LIMITATIONS IMPOSED UPON SENSIBILITY.—On account of this factor of uncertainty in the indications of scales of certain types and especially in the case of check-stabilized scales, it has necessarily been the regular practice, in order to give such a scale a satisfactory and practical definiteness of rest point, to tolerate a low sensitiveness, since, when a scale is very sensitive, uncertainties of indication appear as distinct deviations of the pointer or weighbeam from a given plane of balance in repeated weighings of the same load. The reason for this condition lies in the fact that in a very sensitive scale the restoring forces—that is to say, those forces which tend to propagate the oscillations—may be actually smaller than the resisting force of the static friction opposing the motion. When this condition obtains, the scale may even take up any rest point indifferently, appearing to be in neutral equilibrium, while in point of fact the mechanism is geometrically stable, and capable of executing harmonic vibration if the frictional forces could be withdrawn.

The inherent sensibility of a scale apart from the effects of static friction is usually capable of adjustment to almost any desired value; but it is obvious that if the virtual sensibility be so high that the scale is sensitive to a far smaller quantity than it will *repeat* to in successive weighings, no advantage is had. Rather, the result is disadvantageous in that the user will be confused, and not knowing the cause of the discrepancy he will distrust the scale for any work, even work of a requisite precision sufficiently low that the scale may be entirely suited to it.

On this account scales of this sort having considerable static friction are commonly adjusted to be so insensitive that the deviations from constancy of rest point can hardly be detected by the eye unaided by some special means adapted to magnify the deviations of the indicating element. It has hitherto been erroneously assumed that this low sensitivity was a fault inherent in the general type of check-stabilized scales, but as here indicated it has been necessitated solely by the failure of the scale, on account of friction, to return to the same position of balance under a constant value and disposition of load.

III. ELIMINATION OF FRICTION IN THE STABILIZING CHECK

1. PRIOR TYPES OF FRICTION-REDUCING STABILIZING CHECKS.

The generality of application of this principle of uncertainty of rest point in a scale having appreciable static friction now being recognized, it will be well to note briefly the expedients which have been devised in attempting to reduce the friction arising in the stabilizing check. In Figs. 9, 10, and 11 the principal means which have been resorted to with the object of reducing this friction are shown and described. None of these expedients has proved thoroughly satisfactory; the reasons will appear upon a study of the figures and the legends which accompany them.

2. THE PRESENT DESIGN OUTLINED AND APPLIED.

Figs. 12 and 14 illustrate the application of the present invention to two common kinds of check-stabilized scales, the so-called postal type with sliding poise and the equal-arm, stabilized-pan counter scale. It will be seen that the platform has been so disposed as to lie entirely to one side of the load knife-edge. The effect of this is that stresses in the stabilizing check are always in the sense of tension. The usual stabilizing check is replaced by a flexible elastic tape or wire (or a plurality of such tapes or wires) having a free length between the faces of the clamps at its ends, equal to the distance between the contact lines of the fulcrum and load knife-edges. Now, since provision has been made that the stabilizing check will always be under tensile stress, the tape will be taut and the mechanism "force-constrained."

Furthermore, since the tape is elastic, the energy absorption in it as the scale oscillates is practically zero, and this condition will hold for any position of the load on the platform, so long as such position of the load does not induce in the tape a stress in excess of the elastic limit of the material.

General Principles of Design.—The displacement of the load to be weighed, from the position of minimum stress in the check rod to the position of maximum stress, will have practically no effect on the flexural elasticity of the tape, and the only friction attendant upon the stabilizing device is the very small molecular friction which has usually been termed "mechanical hysteresis." As is well understood, this is very small in amount in the case of more elastic metals and in scales constructed in the manner illustrated,

PRIOR TYPES OF FRICTION-REDUCING STABILIZING-CHECKS.

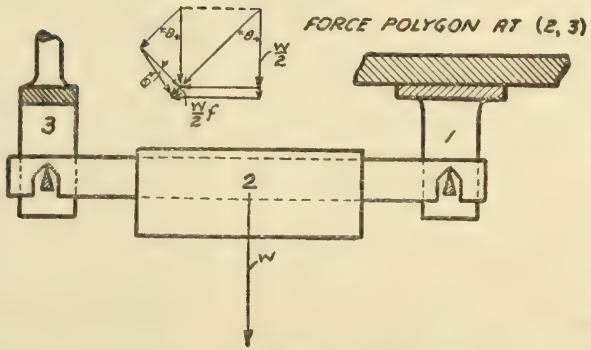

FIG. 9.—*This type of check rod has a V-bearing at each end, engaging with a knife-edge having its axis vertical*

Its capacity to sustain longitudinal loads is determined as in the force diagram shown; this capacity is very small, making the device useful only in one or two restricted applications.

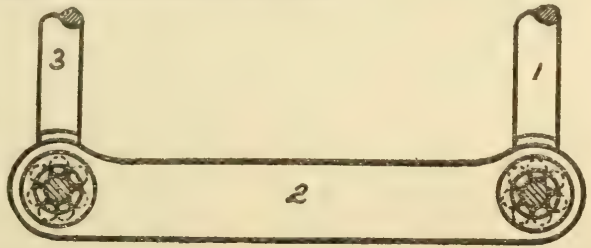

FIG. 10.—*Ball bearings used for the pivots (1, 2) and (2, 3)*

Requires accurate machine work and careful adjustment, and is susceptible to the effects of dirt and corrosion. Moreover, the friction of ball bearings, under the best conditions, is much greater than that of analogous knife-edge or flexure-plate constructions.

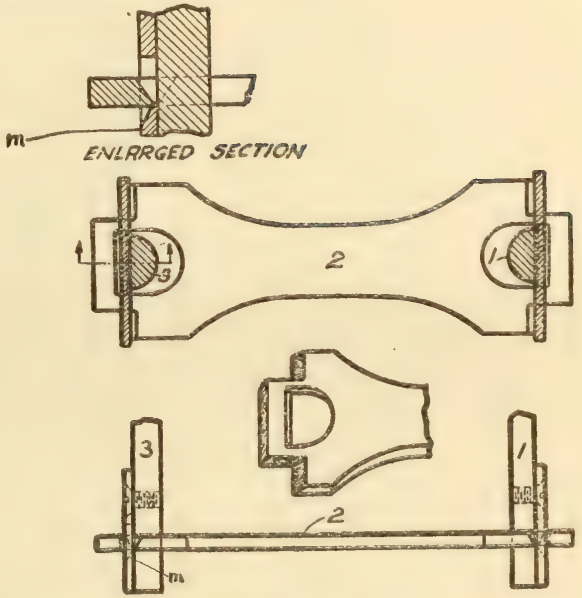

FIG. 11.—*Pairs of opposed knife-edges at each end, in contact with coplanar vertical bearing faces*

An additional knife-edge at each end must be provided at *m* to support the weight of the check rod at the proper center of rotation. The enlarged section shows the effect of end shake and wear in introducing a cramping or binding action.

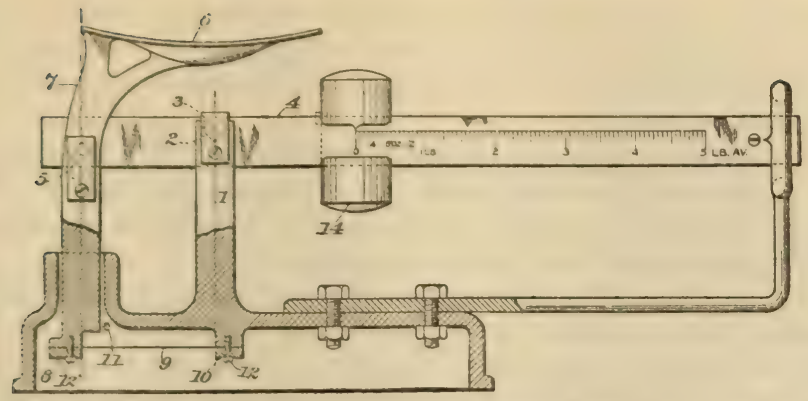

FIG. 12.—*Unequal-arm postal scale, similar in general design to that shown in Fig. 4, but equipped with the author's new stabilizing-check*

The pin *11* is for the purpose of detaining the lower end of the platform stem, so as to prevent buckling of the tape, in case the scale is violently jarred, or handled in such a manner as to turn the platform structure in the counterclockwise sense.

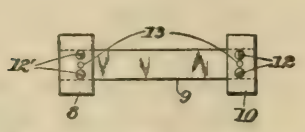

FIG. 13.—*Plan view of tape and clamps*

At *13* are shown pins driven in to retain the tape permanently in position, independent of the friction of the clamps.

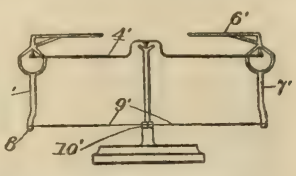

FIG. 14.—*Diagrammatic representation of an equal-arm beam scale, equipped with the new stabilizing-check*

This is similar to the scale shown in Fig. 5.

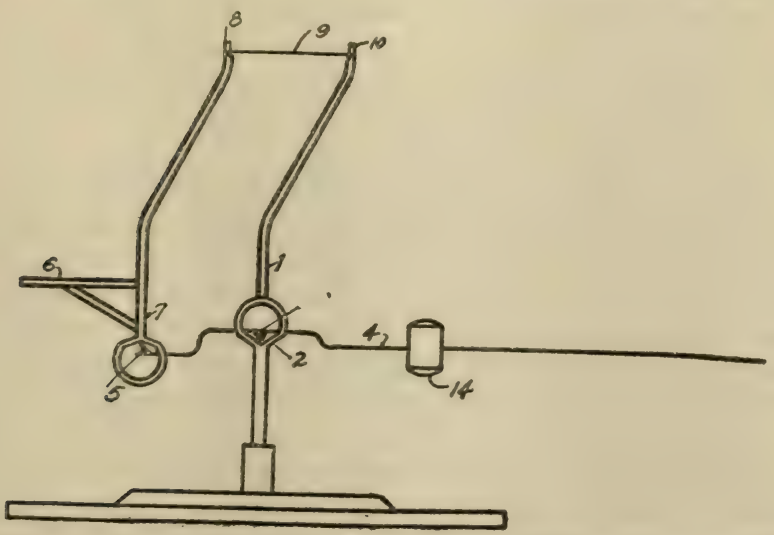

FIG. 15.—*Illustrating the application of the elastic stabilizing link to a scale in which the stabilizing element is above the plane of the beam*

certainly of an order not greater than the knife-edge friction. At any rate, this friction will be entirely negligible for any commercial application of the scale and probably in any ordinary laboratory application as well.

A study of the information at present available on the phenomena of mechanical hysteresis enables us to suggest the direction in which designers of weighing scales may seek to obtain a minimum energy absorption from this cause, as follows:

The tape should be thin in proportion to its width, in order that purely flexural stresses may be small, that the effective center of relative motion at each of the joints (*1*, *2*) and (*2*, *3*) of Fig. 2, may be as definite and as near to the clamp faces as possible, and that the effect on the sensitiveness of the scale of the temperature coefficient of Young's modulus may be negligible. The opposing faces of the clamps which secure the tape are to be straight and parallel to the knife-edges of the beam, while the tape should be so adjusted in its clamps that its whole width is under approximately uniform stress.

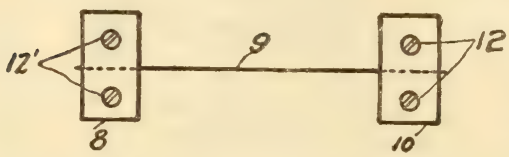

FIG. 16.—*Illustrating the use of a wire in place of a tape, as the stabilizing link*

This construction may be desirable in scales of very small capacity.

The tape should be of most elastic material—e. g., tempered carbon steel—unless for certain commercial applications incorrodibility be so essential that the highest elasticity may be sacrificed for endurance in humid or acid atmospheres, in which case any of the strong and elastic bronzes will serve well. Steel tapes, of thickness from 0.001 inch up and of various widths, are available commercially at low cost.

Knife-Edge Reactions Inclined.—It will be seen in Fig. 17 that the load and fulcrum knife-edges are somewhat inclined toward the quadrant opposite the platform, the purpose of this being to approximate the mean position of the reactions at these knife-edges so that the scale will be as nearly as possible immune against slipping of the knife-edge on its bearing in a direction perpendicular to the line of the pivot. No rational method can be given for the choice of the angle of inclination of the knife-edge, since the determination of the most favorable angle will depend upon the manner of weighing and the bulk of the material weighed; but it is hardly to be recommended that the knife-edge be inclined in the

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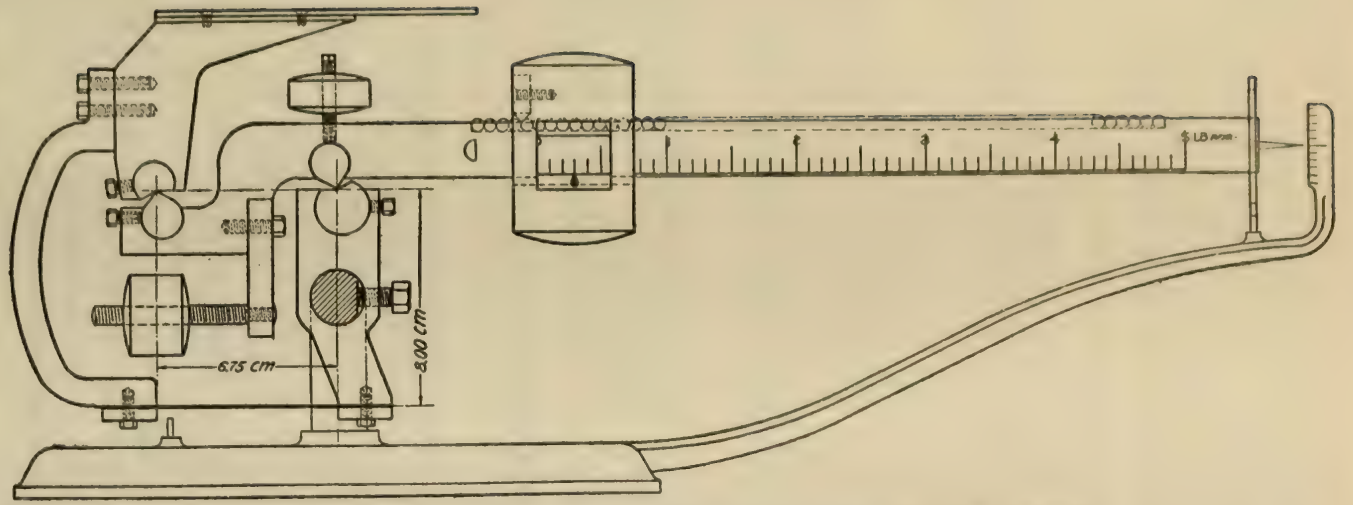

FIG. 17.—*Unequal arm beam scale with sliding poise, comprising the present invention*

This scale was built for experimental purposes in the shop of the Bureau of Standards. In this scale the knife-edges and bearings have been made adjustable to various inclinations, so as to permit of studying the slipping of knife-edges in their bearings in a direction transverse to the knife-edge axes. The beam of this scale comprises a novel form of notch provision devised by the author, to establish with exactitude the increments of motion of the sliding poise, the notches being constituted by the contiguous surfaces of the upper hemispheres of a row of steel balls set in a straight line and making contact with each other along that line. The extremely high accuracy of commercial bearing balls to equality of diameter and sphericity affords an ideally accurate notching, which will not require the tedious, point-by-point adjustment by hand, which has formerly been requisite in the case of accurate weighing scales having notched beams. It has been impossible in the case of track scales, for example, to machine the usual triangular notches accurately enough to eliminate the necessity of subsequent hand adjustment.

direction of the mean reaction for the full load of the scale displaced to the extremes of the platform, since the full load equivalent to the capacity of the scale would commonly be of such bulk in relation to the dimensions of the platform that it could not be so far displaced from the center. A better basis will be to determine the mean or mid-direction of the reaction for a load equal to one-half the capacity of the scale, when the center of gravity of the load is displaced from the extreme left edge of the platform to the extreme right edge of the platform, taking proper account of the weight of the platform itself.

From equation 1 on page 8 it is deducible that the pan structure need not lie entirely to the one side of the vertical plane through the load knife-edge, since, in order that the tape remain in tension for all loads and for all positions of any load, it is necessary only that the center of gravity of the pan element and load combined, lie on the proper side of the vertical plane through the load knife-edge, to produce a moment of such sense that it can be resisted by a finite tensile stress in the stabilizing tape. In equation (1) this is equivalent to a requirement that T be positive and greater than zero.

For the designing of this type of scale (and the same applies to many other sorts as well) it should be said that the graphical method will ordinarily be the most useful, being the simplest, and suggestive of the true sense of the several forces and moments involved. Fig. 2 shows the graphic analysis of the forces, giving solutions for the magnitudes and directions of the reactions at (*3*, *4*) and (*4*, *1*).

Since in the present design the constancy of direction of the reaction in the check rod is assured, it will be possible and practicable, if for any reason it appear desirable, to use knife-edges in the stabilizing mechanism; and the difficulty to which attention was directed in the legend of Fig. 11 will not exist. A single pair of opposed, horizontally directed knife-edges, acting at each extremity of a simple flat bar slotted so as to establish suitable V-bearings, will serve to provide a mechanically satisfactory stabilizing link. It is doubtful, however, whether such an arrangement will show any advantage over the flexible tape, the latter being easier to adjust and assemble and not liable to derangement by the accidental disengagement of the parts.

IV. ADJUSTMENT OF THE SCALE

The adjustment of this type to correctness of reading may be considered to comprise the following individual adjustments:

1. Adjustment of the ratio of lever arms of the beam if the beam has three knife-edges; or adjustment of the weight of the sliding poise to correspond correctly to the distance between the load and fulcrum knife-edges in case the beam has but two knife edges.

2. Adjustment of the linkwork so that the *accuracy of indication* is independent of the position of the load on the platform.

3. Adjustment of the linkwork so that the *sensibility* of the scale is independent of the position of the load on the platform.

1. ADJUSTMENT OF RATIO OF LEVER ARMS

The first of these adjustments is common to all types of lever scales, and consists merely in adjusting the spacing of the pivots or knife-edges so that the actual arm-ratio of the beam is in agreement with the figured arm ratio, the details of the adjustment depending upon whether the scale is equipped with a hanging counterpoise suspended on a pivot at the end of an invariable arm or is equipped with a fixed-weight sliding poise establishing a variable lever arm. This adjustment is a matter of manufacturing detail and needs no discussion here.

2. ADJUSTMENT OF PARALLELISM OF LINKS.

The second and third of the adjustments named above are not of equal importance. Clearly, since the load to be weighed can in practice never be exactly centered on the platform, it is the first essential that the scale be so adjusted that the reading of the weight of the load obtained is independent of the position of the load. This adjustment requires that the two horizontally directed[2] bars (Fig. 18) of the figure *1234* be exactly parallel. Fig. 18 shows the reason for the variation in reading obtained when these bars, *2* and *4*, are not parallel. It will be seen that, under these conditions, the stabilizing check is subjected to a force which has a vertical component depending in magnitude upon the position and value of the load upon the pan. The effect of this vertical com-

[2] In the following discussion the beam and the bars *2* and *4* of the quadrilateral are for convenience spoken of as horizontal, and the bars *1* and *3* as vertical; this is, however, nonessential, being adopted because of the usualness of this design, and for simplicity. The reasoning can be generalized to include any definite, recurring null position, whether inclined or not.

ponent is to increase or decrease the apparent weight of the load as the vertical component of the reaction is directed upwardly or downwardly. If the links *2* and *4* were parallel, no upward or downward component would appear in the reactions at the points of connection of the stabilizing link when the scale beam was in its horizontal or null position.

We may now consider the third requirement of adjustment. It will be appreciated that this requirement is not of paramount importance in the case of commercial scales, since practically all such are read by the null method, the beam being equilibrated in the process of weighing so as to come to rest at or swing in equal arcs about the horizontal position. This being the case, no moderate variation in sensibility can have serious effect, provided that all values of the sensibility are high enough to meet the requirements of the work for which the scale is to be used.

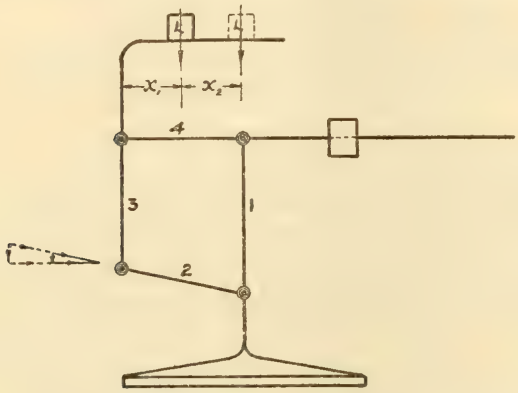

FIG. 18.—*Faulty adjustment, links 2 and 4 not parallel*

The effect of this condition is to introduce at the joint (*2, 3*) a reaction having a vertical component, as resolved in the force triangle shown in the figure, the value of this component depending upon the magnitude and position of the load on the pan and upon the sense and amount of the inclination of the link *2*. This vertical component acts to increase or decrease the apparent value of the load being weighed, according as the component acting on link *3* is directed downwardly or upwardly.

It will be seen in Fig. 19 that, so long as the beam is read in the horizontal position, the reaction at the point of connection of the stabilizing check is horizontally directed; since no vertical component exists, the force at the load knife-edge imparted by any increment of load when the beam is in that position is independent of the position of the load. Moreover, it will be seen that as soon as the beam is deflected from the horizontal position, the bars *2* and *4* being unequal in length do not move in parallel paths but become inclined to each other so that a vertical component of the reaction is set free. This, it is to be understood, affects the restoring moment of the weighing system, of which the sensibility is the direct function, and if the scale were to be read by deflections, as is a precision balance, serious error might result, since the load equivalent of a given angular deflection from the position

of balance would depend upon the position of the load on the platform. It will be seen, also, that if the load and counterpoise weights are varied by trial, as in the ordinary process of weighing, so that the beam finally comes to rest in the horizontal position, no error will result, as in this position no vertical component of the tension in the tape exists.

In a very sensitive scale of this type, difficulty might rarely be encountered on account of the above-described deviation from constant sensibility, in that, for certain positions of the load on the pan, the scale might become unstable or accelerating, which is merely a condition of negative sensibility occurring when the point of neutral equilibrium (infinite sensibility) has been passed.

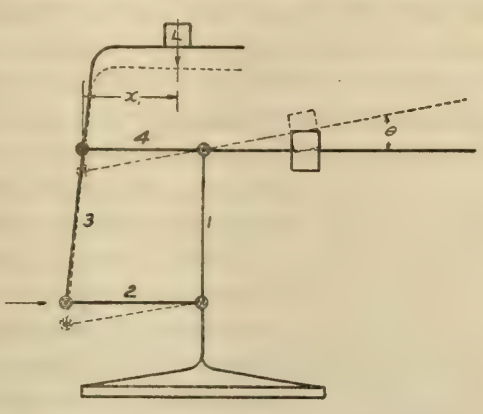

FIG. 19.—*Faulty adjustment, links 1 and 3 not parallel*

Since, under this arrangement, links *2* and *4* are parallel when the beam is horizontal, no error is introduced so long as the beam is read in this position, as no vertical component of the reaction at (*2*, *3*) appears. However, when the beam is deflected, links *2* and *4* no longer remain parallel, and the vertical components at the joints (*2*, *3*) and (*3*, *4*) are unequal, leaving a net free component either increasing or decreasing the effect of the load in returning the beam to its null position. As explained in the text, this status practically affects only the sensibility of the scale, when the position of the load on the platform is altered.

The above is of significance chiefly in showing that the adjustment of the bars *1* and *3* to exact parallelism is of minor importance and hardly of consequence in commercial scales. It is on account of this fact that in the new type of stabilizing element presented in this paper, the slight displacement of the centers of relative motion in the tape, toward its center, due to such rigidity as it possesses, is of little importance, and need not be more than approximately and empirically corrected for. This slight displacement of the centers (*1*, *2*) and (*2*, *3*) away from the faces of the clamps can be compensated for by making the distance between the inner faces of the clamps slightly in excess of the distance (*3*, *4*)–(*4*, *1*).

Some elastic effect will be introduced by the stiffness of the tape, especially when the tapes are made relatively thick to withstand large loads or hard usage, but no difficulty will be encountered on this account, as the additional restoring moment coming from

the resilience of the tape can be compensated for by suitable reduction of the restoring moment of the beam, by adjusting its center of gravity closer to the fulcrum knife-edge, or even in extreme cases, should it prove necessary, by locating the center of gravity of the beam above the fulcrum knife-edge.

3. MAKING THE ADJUSTMENT SECURE.

After the adjustment of the tape is completed so that the effective length between centers of flexure is equal to the distance between the load and fulcrum knife-edges of the beam, some means should be applied to maintain this adjustment permanently against the shocks of handling incident to use. While, during the process of adjustment, the tape is firmly held by the friction of the clamps, the permanency of the adjustment after its completion may be assured by tightening the clamping screws or bolts, then grinding off the screw-driver kerfs or locking the nuts in some convenient way. Next, holes are drilled through both jaws of each clamp, and into these holes are driven tightly fitting pins, the outer ends of which are ground off flush with the surfaces of the lower clamp jaws. This arrangement will serve to secure the tapes against gradual slippage or sudden release under the friction of the clamps. Other means of performing the same service are familiar to makers of cam scales, in which the ends of the tapes must be securely attached to the cams upon which the tapes wind.

V. CONCLUSIONS

The stabilizing device described in this paper has many useful applications. Its elements are of the utmost simplicity, and its construction and adjustment offer no peculiar difficulties. Its manufacturing cost should be little, if any, in excess of that of the earlier types, while the broadness and utility of the applications of check-stabilized scales are thereby much enhanced.

1. LIMITATIONS ON SENSIBILITY LARGELY REMOVED.

On account of the fact that the designer is not limited to a low sensibility by the presence of a considerable friction which will mask the indications of the scale and make a high virtual sensibility of no practical value, the present design permits the application of the convenient and compact check-stabilized scale to uses from which its deficiencies have hitherto excluded it.

For example, druggists' counter scales and even prescription scales can be made in accordance with the designs herein set forth; while in the laboratory, where the unsatisfactory "trip scale" and the combination check-stabilized and four-point-support stabilized scale, long known as the "union" scale, have been much used for the weighing of large samples outside the capacity range of the available suspended-pan analytical balances, the present design will perform a useful service.

Moreover, its utility is not limited to these relatively large capacities, for, by making the stabilizing element of very flexible and elastic construction, as will be attainable by the use of a quartz fiber, or a plurality of such fibers, the utmost delicacy of action can be secured without sacrifice of accuracy, provided only that the finish and accuracy of adjustment of knife-edges and bearings be of the same high order as would be required in a suspended-pan balance for work of equal precision.

Most of the computing and other automatic scales used in retail trade, except the common hanging-pan spring scale, are of the check-stabilized type, and the friction of the old type check rod has been a source of serious difficulty on account of the limits it imposed on the delicacy of action of the scale, preventing the scale from accurately repeating the reading at a given load. The present design can be readily applied in the construction of these scales, as well as to the nonautomatic types hereinbefore discussed. In many of these computing scales, in order to obtain as great a length as possible for the vertically disposed sides of the parallelogram, the check rod has been placed high above the platform, so that the greater space available in the upright structure of the scale could be used to house the long platform stem and the fixed link. The present design lends itself quite as well to this arrangement, using the above-platform disposition of the stabilizing link, and such a modification of the mechanism is illustrated in Fig. 15; for simplicity, the application there shown is a nonautomatic scale.

2. IMMUNITY FROM EFFECTS OF DIRT AND CORROSION

In cases where the scale is exposed to much dirt or moisture or corrosive fumes the tape can be made of some nonrusting material of suitable elastic properties, or, if it is found desirable to use steel, it can be perfectly protected by a strong coating of elastic varnish or lacquer or perhaps by electroplating. The scale will

be better protected against deterioration under these severe conditions than any of the previous types, in any of which latter a slight accretion of rust or foreign matter upon the turning pairs of the check rod may easily cause a serious binding and derangement of the scale. An examination of Figs. 9, 10, and 11 will show the susceptibility of these earlier types to the effects of dirt and corrosion.

3. INCREASE IN CAPACITIES FEASIBLE

The scale we have described can be used for higher capacities than the old type; in fact, its use can be extended into the field usually considered solely satisfied by the four-point-support type of stabilized platform scale, the reason being that the practical absence of friction in the stabilizing element will permit scales of large capacity to be produced without restriction to the very small platform dimensions that would be requisite in the older forms in order to keep the frictional moments reasonably low.

In this connection, attention should be called to the fact that the general type of stabilized scale here considered, whether using the rigid or the elastic stabilizing link, is exposed to derangement when the platform load is large and far displaced, due to the slipping of the load knife-edge (or less probably the fulcrum knife-edge) within its bearing, destroying the parallelism of the linkwork. The effect is, of course, due to the growth of the component of the knife-edge reaction in the direction of the contiguous face of the bearing to a value larger than the static friction of the knife-edge against sliding in a direction perpendicular to the pivot axis. Two means are suggested for reducing the likelihood of this occurrence, although it should be borne in mind that the condition named will not ordinarily arise except in the case of abnormally large platforms or large weighing capacities.

Assuming that the angle of the bearing has been well adapted to the angle of the knife-edge, and the knife-edge properly inclined in accordance with the mean obliquity of the reactions, the most useful expedients to eliminate the appearance of the difficulty named appear to be the following:

1. The use of an arrestment, as is common in foreign-made scales of every sort, adapted to return the load and fulcrum knife-edges accurately to their proper contact lines before each weighing. Such a device also has the effect of greatly increasing the life of a scale, in that it protects the knife-edges from wear, except at such times as loads are actually being weighed.

2. The use of flexure plates instead of knife-edges, similar to the designs of A. H. Emery, as used in his testing machines and railroad track scales. By the use of this form of pivot, the relation of pivot to bearing, and consequently the constancy of the parallelogram adjustment, would be definitely assured under all conditions of loading. So constructed, the scale would have flexural pivoting throughout for both load-supporting and load-stabilizing functions, an interesting generalization from the device which forms the subject of this paper.

The commercial advantages of the scale described may be recapitulated as follows: The limitations hitherto imposed on the attainment of a high sensibility have been practically set aside, whereby the convenient and compact check-stabilized scale has been made available for a wider range of use; the new type of construction is less susceptible to the effects of dirt and corrosion; and finally, it can be used for scales of greater capacities and greater platform dimensions than was possible in the case of antecedent forms of the check-stabilized scale.

WASHINGTON, June 28, 1917.

Appendix.—COPY OF PATENT

UNITED STATES PATENT OFFICE

FREDERICK J. SCHLINK, of Washington, District of Columbia.

WEIGHING-SCALE.

[1,218,902. Specification of Letters Patent. Patented Mar. 13, 1917. Application filed July 22, 1916. Serial No. 110,804.]

To all whom it may concern:

Be it known that I, FREDERICK J. SCHLINK, a citizen of the United States, and an employee of the Bureau of Standards, United States Department of Commerce, a legal resident of the State of Illinois, residing in the city of Washington, in the District of Columbia, (whose post-office address is 1425 T street, NW.,) have invented new and useful Improvements in Weighing-Scales, and have made application by petition of even date herewith, under the act of March 3, 1883, chapter 143, (22 Stat., 625,) praying that Letters Patent therefor may be granted to me.

The invention herein described and claimed may be used by the Government of the United States or by any of its officers or employees in the prosecution of work for the United States, or by any person in the United States, without payment of any royalty thereon.

The following is the specification of the invention:

My invention relates to an improvement in stabilizing devices for weighing scales.

The object of my invention is to provide a stabilizing mechanism for a scale pan or platform sensibly free from friction and not subject to the relative large and variable frictional resistances which occur in scales equipped with the usual forms of stabilizing devices.

The stabilized scale is usually distinguished by having a platform or pan located above the knife edges in the weighing beam or lever, and the mechanism for stabilizing said pan and constraining it to move in parallel planes is called the stabilizing mechanism. In the ordinary forms which are familiar in the numerous postal and package scales of small and moderate capacity the stabilizing link or element is a simple flat bar provided at each end with holes through which respectively pass pins connecting the bar at one end to a fixed part of the scale and at the other to the vertical stem supporting the platform. The length of this link between centers of pin holes, in order that the weight indicated shall be independent of the position of the load on the platform, is required to be equal to the distance between the load and the fulcrum knife edges of the beam. The pins at either end of the link form pivots. When the load on the platform is displaced from the center of said platform in the direction of the longitudinal axis of the beam, a stress is set up in the stabilizing link accompanied by reactions at each of the pivots above mentioned, and for all such non-central placement of the load a considerable and variable friction will be introduced at these connections, this friction being much greater in amount than that existing between the usual knife edge and bearing, thus acting to reduce the accuracy of the scale, and to limit the sensitiveness which is attainable under the given construction. My invention relates to a means of overcoming this difficulty by providing a stabilizing element which is sensibly free from friction and which leaves the scale unaffected as to accuracy and sensitiveness by variation in the position of the load upon the platform.

The nature, characteristic features, and scope of my invention will be more readily understood by the following description taken in connection with the accompanying drawing.

In the drawings: Figure 1 is an elevation in partial section of a typical postal scale embodying my invention. Fig. 2 is a view from below of the elastic tape used as the stabilizing element, in connection with the clamp at each end thereof, by means of which the tape is secured. Fig. 3 illustrates schematically the application of my invention to the so-called "trip scale" or equal-arm stabilized pan balance such as is in common use in trade.

Referring more particularly to the drawing: 1 indicates the post which supports the fulcrum bearing 2 in which the fulcrum knife edge 3 of the beam 4 is pivoted. The beam carries a sliding poise 14 and the usual scale of graduations. The load knife edge is shown at 5 and may if necessary be somewhat inclined in a direction away from the scale platform 6, the latter being carried on a supporting stem 7, which at its lower end receives by a suitable clamp member 8 one end of the tape (or wire) 9. The clamp member 8 is secured to the stem by means of the screws 12'. The other end of the tape is received beneath the clamp member 10 which is secured to the base of the scale by means of the screws 12. The pan or platform 6 is so located as to lie entirely to the one side, namely, that nearest the fulcrum knife edge, of the load knife edge 5. It thus results that tensile stresses only are produced in the tape 9 for all positions of the load on the platform. The distance between the proximate faces of the clamp members 10 and 8 is substantially equal to the distance between the contact lines of the fulcrum knife edge 3 and the load knife edge 5 while the distance between the contact line of the fulcrum knife edge 3 and the line of entry of the tape beneath the clamp member 10 is equal to the distance between the line of contact of the load knife edge 5 and the line of entry of the tape beneath the clamp member 8. A pin may be provided as at 11 to prevent buckling of the tape, in case, by accident or from any other cause, the lower portion of the stem supporting the pan should be displaced toward the member 10.

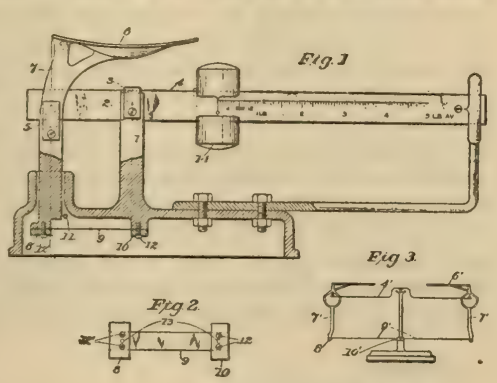

FIG. 20.

Suitable means may be added for permanently securing the tape after adjustment so that it may not be subject to the danger of displacement through accident or shock. In Fig. 2 the screws by which clamp members 8 and 10 are held in position may pass through close-fitting holes in the tape or may act to secure the tape ends by friction between the clamp jaws alone. The pins 13 may after final adjustment of the tape be driven tightly into holes drilled completely through clamp jaws and tape so as to provide a positive, and not easily alterable, means of preventing slippage or displacement of the tape during use of the scale.

The thickness and width of the tape are chosen so as to be suitable to the loads and service the scale will be subjected to. I do not wish to be limited to the use of a single tape for the purpose.

It is to be noted that some elastic effect will be introduced by the stiffness of the tape, especially if the tape be made relatively thick in order to withstand large loads, but no difficulty will be experienced on this account as the additional restoring moment provided by the elasticity of the tape can be compensated for by suitable

reduction of the restoring moment of the beam, by adjusting its center of gravity close to or even, if it should in rare instances prove necessary, by locating it above the fulcrum knife edge.

In Fig. 3 in which an equal-arm balance is shown, 4′ is the scale beam having the load knife edges at either end, each of which support the stem 7′, a tape 9′ being connected to the lower end of each stem.

It is understood that it is not essential that the stabilizing tape be below the plane of the beam. The arrangement may be such that the stabilizing tape is above the plane of the beam or in fact in any plane except that defined by the load and fulcrum knife edges. In case the stabilizing tape lies above the plane of the load and fulcrum knife edges, the particular side toward which the scale platform is disposed may differ from the arrangement illustrated in the drawings. In any case the disposition of the platform will be such that the stress introduced in the tape will be in the sense of tension.

Although but two specific embodiments of this invention have been herein shown and described, it will be understood that numerous details of the construction shown may be altered or omitted without departing from the spirit of this invention as defined by the following claim:

In a weighing scale, the combination with the scale beam of a load supporting member pivotally connected to the beam at one side of the fulcrum of the beam, said member having its load receiving platform so disposed with reference to said pivot that the center of gravity of the system including the said member and the load placed upon its load receiver will always lie on a given side of the vertical plane through the pivot axis, said member extending away from the plane of said load pivot and fulcrum and a flexible tape so connected at one end to said member at a point outside the plane of said pivots and at the other end to a stationary part of the scale as to afford a free portion of the tape between the points of connection substantially equal in length to and, under tension parallel with, a straight line terminating in the axes of the above-named pivot and fulcrum and perpendicular to such axes.

Signed at Washington, D. C., this 21st day of July, 1916.

FREDERICK J. SCHLINK.

Witnesses:

C. A. BRIGGS,

LOUIS A. FISCHER.

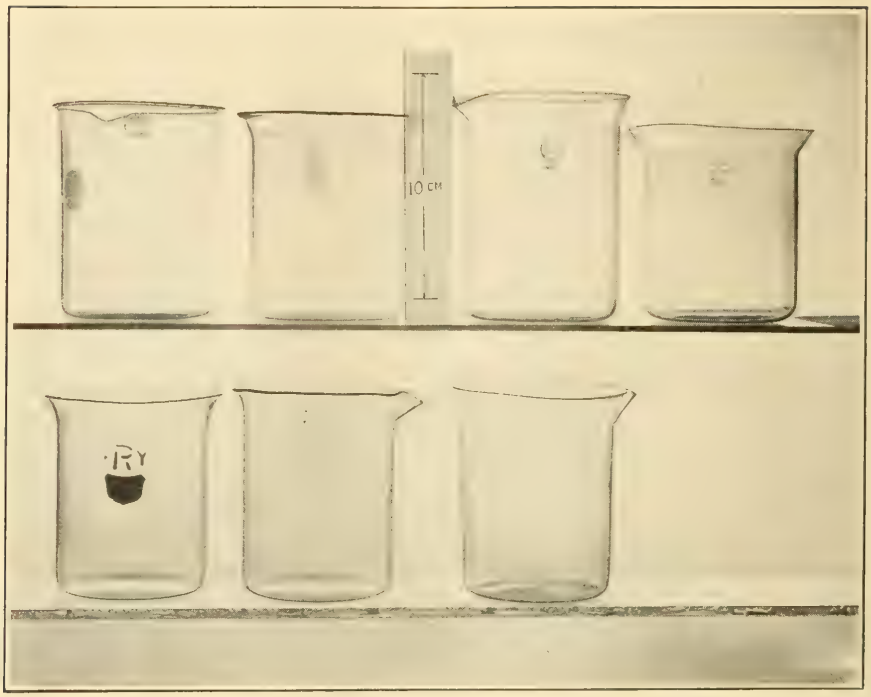

FIG. 1.—*Beakers*

DEPARTMENT OF COMMERCE

TECHNOLOGIC PAPERS

OF THE

BUREAU OF STANDARDS

S. W. STRATTON, DIRECTOR

No. 107

COMPARATIVE TESTS OF CHEMICAL GLASSWARE

BY

PERCY H. WALKER, Chemist

and

F. W. SMITHER, Associate Chemist

Bureau of Standards

ISSUED APRIL 5, 1918

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COMPARATIVE TESTS OF CHEMICAL GLASSWARE

By Percy H. Walker and F. W. Smither

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I. INTRODUCTION

Prior to the summer of 1914 the greater part of the chemical laboratory glassware used in this country was imported from Germany and Austria.

The cutting off of imports from these countries caused a very serious shortage of glassware in this country, which is not yet entirely overcome. However, within the past two years a number of American manufacturers have increased their production of such ware, or are manufacturing grades of chemical glassware that they did not produce before. It is probable that practically our whole available supply at this time is of domestic manufacture, much of which is ware sold under brand names which were unknown a short time ago. In order to furnish to chemists information regarding such domestic brands, it was decided to compare them with those of foreign make.

II. MATERIALS EXAMINED

1. SOURCES AND IDENTIFICATION

No information of real value can be obtained from glassware which does not bear a manufacturer's permanent trade-mark, a jobber's trade-mark being of practically no value. There are, therefore, included in these tests only brands which bona fide manufacturers are willing to openly claim as their products. Two kinds of foreign ware (Jena and Kavalier) were included for purpose of comparison, since these represent what has been generally considered high-grade ware of the two most commonly used types. The five brands of domestic ware included all that were known to bear manufacturer's trade-marks, though it is possible that others may now be on the market. Beakers and flasks of the different makes which approximated, in size, the 400 cc Jena beaker and the 400 cc Jena flask were selected.

2. KINDS OF PIECES TESTED

The following details serve to establish the history of the samples so far as known to us. Unless otherwise stated the wares were purchased in the open market.

Kavalier.—Thirty-nine beakers (400 cc) were received December 17, 1915 (one broken). Nine beakers (400 cc) were received January 3, 1916. No flasks could be secured.

Macbeth Evans Glass Co.—Forty-eight beakers (400 cc) were received January 21, 1916 (one broken, one cracked, one with lip broken). Forty-eight flasks (400 cc) were received January 21, 1916.

Pyrex.—Forty-eight beakers (400 cc) were received December 17, 1915 (one with lip broken). Forty-eight flasks (400 cc) were received January 3, 1916.

Jena.—Forty-eight beakers (400 cc) were received December 17, 1915. A uniform set of flasks could not be purchased at that time and 48 flasks (400 cc) were selected from stock on hand in the Bureau of Standards.

Nonsol.—Forty-eight beakers (350 cc) and 48 flasks (250 cc) were received January 3, 1916.

Fry.—Forty-eight beakers (400 cc) and 48 flasks (400 cc) were received January 3, 1917.

Libbey.—Forty-eight beakers (400 cc) and 49 flasks (300 cc) were received March 30, 1916.

FIG. 2.—*Flasks*

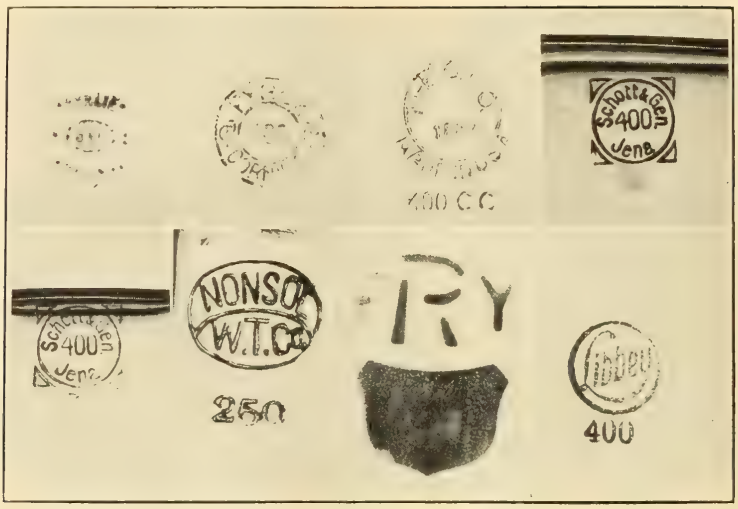

FIG. 3.—*Brand marks*

Fig. 1 is a photograph of representative beakers and Fig. 2 of representative flasks, showing the brand marks. Fig. 3 shows the brand marks on a somewhat larger scale.

Table 1 summarizes observations made on the wares as received. The capacity as claimed and as determined from one sample chosen at random is given. Each sample was weighed and the average, maximum, and minimum weights are given.

TABLE 1 .—Data Regarding Glassware

BEAKERS

Trade-mark	Capacity		Weight		
	Claimed	Determined	Maximum	Minimum	Average
	cc	cc	g	g	g
Kavalier N (B&L) S Bohemia	400	410	76	42	54
M. E. G. Co. 1887 Made in USA 400 cc	400	420	94	57	77
Pyrex 400 Corning	400	405	133	62	82
Schott & Gen 400 Jena	400	425	76	51	60
Nonsol W T Co 350	350	405	67	42	52
Fry	400	390	76	48	60
Libbey 400	400	475	77	46	61

FLASKS

Trade-mark	Capacity		Weight		
	Claimed	Determined	Maximum	Minimum	Average
	cc	cc	g	g	g
M. E. G. Co. 1864 Made in USA 400 cc	400	465	86	64	74
Pyrex 400 Corning	400	425	90	70	79
Schott & Gen 400 Jena N	400	450	78	49	66
Nonsol W T Co 250	250	310	55	44	50
Fry	400	440	89	55	68
Libbey 300	300	340	66	40	51

III. COMPOSITION

1. METHODS OF CHEMICAL ANALYSIS

In the main, the procedures recommended by Hillebrand [1] were followed, making blank determinations on the reagents.

Silica, Alumina, Iron Oxide, Zinc Oxide, Lime, and Magnesia.—One gram of the powdered sample was fused with anhydrous normal sodium carbonate and silica determined, eliminating boric acid by the addition of methyl alcohol and hydrochloric acid.[2] Platinum and other metals precipitable by hydrogen sulphide were removed from the filtrate from the silica by means of hydrogen sulphide and the precipitate was rejected. The filtrate was oxidized with potassium chlorate and the iron and aluminum were precipitated three times with ammonia, washing each time with 2 per cent ammonium chloride solution as recommended by Blum.[3] Small amounts of iron and aluminum were recovered from the combined filtrates. The silica in the ignited oxides was recovered and the iron was determined by reducing with hydrogen sulphide and titrating with permanganate. The alumina was obtained by difference, after deducting the recovered silica, and phosphoric anhydride if present.

In the filtrate from the iron and aluminum the zinc was precipitated by hydrogen sulphide by the formic-acid method of Waring.[4] The precipitate was redissolved in dilute hydrochloric acid and the precipitation repeated. The zinc sulphide so obtained was dissolved in dilute hydrochloric acid and the zinc determined as pyrophosphate. In some determinations the zinc sulphide was dissolved in hydrochloric acid, evaporated, and the zinc precipitated by sodium carbonate and weighed as zinc oxide, as described in Treadwell-Hall's "Quantitative analysis." The combined filtrates from the zinc sulphide were evaporated to expel formic acid and any manganese present was precipitated by ammonium sulphide. Zinc was also determined by decomposing a separate portion of the sample with hydrofluoric and sulphuric acids, precipitating as sulphide by the Waring method, and finally igniting the sulphide to oxide.

In the filtrate, calcium was determined by double precipitation and weighed as oxide after correcting for traces of alumina.

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[1] Bull. 422, U. S. Geological Survey, The Analysis of Silicate and Carbonate Rocks.

[2] J. W. Mellor, A Treatise on Quantitative Inorganic Analysis, p. 589 (1913); Jannasch, Z. anorg. Chem., **12**, p. 208, 1896; Z. anal. Chem., **36**, p. 383, 1897.

[3] Determination of Aluminium as Oxide, Scientific Paper No. 286, Bureau of Standards; J. Am. Chem. Soc., 38, pp. 1282–1297; 1916.

[4] J. Am. Chem. Soc., **29**, p. 265; 1907.

Magnesium was determined by double precipitation in the united filtrates from the calcium oxalate and weighed as the pyrophosphate. The precipitate was examined for calcium and manganese.

Alkalies were determined on 0.5 gram of sample by the J. Lawrence Smith method.

Manganese was determined on a 2-gram sample by the bismuthate method,[5] decomposing the sample with hydrofluoric and sulphuric acids. The potassium-permanganate solution was standardized against sodium oxalate.[6]

Arsenic, Antimony, and Lead.—Three grams of the powdered sample were decomposed with hydrofluoric and nitric (or sulphuric) acids according to Mellor.[7]

The cold cake was dissolved in hydrochloric acid and water, heated, a little potassium iodide solution added to reduce the arsenic acid,[8] and saturated with hydrogen sulphide gas. After standing overnight in a corked flask, the precipitate was filtered off and washed with water containing hydrogen sulphide, then treated with hot sodium sulphide solution. The lead sulphide remaining on the filter was dissolved in hot dilute nitric acid, sulphuric acid added, and the lead determined as lead sulphate in the usual manner. The sodium sulphide solution was evaporated nearly to dryness, and the residue was digested with hydrochloric acid and potassium chlorate. In the absence of antimony, the arsenic was determined directly as pyroarsenate by Levol's method.[9] In the absence of arsenic and lead, the hydrogen sulphide precipitate was filtered on a Gooch crucible, washed, dried, ignited in a current of carbon dioxide, and the antimony trisulphide weighed.[10] Antimony was also determined by decomposing the sample by heating with hydrofluoric and oxalic acids as recommended by Sullivan and Taylor,[11] finally weighing as the trisulphide. Arsenic was also determined by decomposing a sample with hydrofluoric and sulphuric acids, transferring to a Gutzeit apparatus, and passing the generated arsine into mercuric chloride solution, finally weighing the mercurous chloride formed.[12] Lead was also determined in the filtrate from the silica obtained by the sodium carbonate fusion method.

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[5] Blair, The Chemical Analysis of Iron, p. 121; 1908.

[6] Blum, J. Am. Chem. Soc., 34, p. 1379; 1912.

[7] J. W. Mellor, A Treatise on Quantitative Inorganic Analysis, p. 271; 1913.

[8] L. L. de Koninck, Bull. soc. belg. chim., 23, pp. 88–94; 1909.

[9] Treadwell-Hall, Quantitative Analysis.

[10] J. W. Mellor, A Treatise on Quantitative Inorganic Analysis, pp. 297–298; 1913; Gooch, Representative Procedures in Quantitative Chemical Analysis, pp. 101–104; 1916.

[11] J. Ind. Eng. Chem., 6, p. 897; 1914.

[12] Claude R. Smith, U. S. Dept. Agr., Bur. of Chem. Circular No. 102; 1912.

Boric Acid was determined by Sullivan and Taylor's modification of Wherry's method.[13]

Sulphuric Anhydride.—One gram of the sample was fused with 6 grams of sodium carbonate, treated with water and hydrochloric acid, and the silica removed in the usual manner by evaporation. Sulphuric anhydride was precipitated in the filtrate as barium sulphate.

Phosphoric Anhydride was determined by the method described by Lunge.[14]

Selenium and *Fluorine* were tested for qualitatively.[15]

2. ANALYSES OF WARE TESTED

The marks on both beakers and flasks were identical in the case of all the wares examined except Jena, in which an "N" appeared below the main body of the trade mark on the flasks but did not appear on the beakers. Therefore, with the Jena ware analyses were made of both beakers and flasks, but with the other wares the flasks were not analyzed. It is evident from the results that there is no difference in composition between the Jena beakers and flasks. Table 2 shows analyses of the wares tested.

TABLE 2.—Analyses

Ware	Kavalier beaker	M. E. G. Co. beaker	Pyrex beaker	Jena beaker	Jena flask	Nonsol beaker	Fry beaker	Libbey beaker
Al_2O_3	0.14	1.0	2.0	4.2	4.2	2.5	2.7	2.1
Fe_2O_3	0.08	0.35	0.25	0.25	0.27	0.23	0.22	0.44
ZnO	.....	5.6	.....	10.9	10.9	7.8	3.6	.....
PbO	.....	.....	.....	.....	.....	.....	.....	1.0
MnO	0.02	0.02	0.01	0.01	0.01	0.01	0.03	0.03
CaO	8.7	0.66	0.29	0.63	0.56	0.79	2.6	0.42
MgO	0.17	4.3	0.06	0.21	0.25	3.4	2.6	0.08
Na_2O	7.1	10.8	4.4	7.5	7.8	10.9	9.8	8.2
K_2O	7.9	0.30	0.20	0.37	0.31	0.30	1.5	0.67
SiO_2	75.9	73.0	80.5	64.7	64.7	67.3	68.6	75.9
B_2O_3	.....	3.6	11.8	10.9	10.6	6.2	8.1	10.8
P_2O_5	0.08	.....	.....	.....	.....	.....	.....	.....
SO_3	0.20	0.02	.....	.....	.....	.....	.....	.....
As_2O_5	Trace	0.02	0.70	0.14	0.19	Trace	0.18	0.36
Sb_2O_3	.....	0.60	.....	.....	.....	0.62	.....	.....
Total	100.29	100.27	100.21	99.81	99.79	100.05	99.93	100.00

Selenium and fluorine were not found, but lithium was detected spectroscopically by Paul W. Merrill in all the samples.

[13] J. Ind. Eng. Chem., 6, p. 899; 1914.

[14] Lunge-Keane, Technical Methods of Chemical Analysis, 1, p. 654; 1908.

[15] Lunge-Keane, Technical Methods of Chemical Analysis, 1, pp. 642–643; 1908.

3. CONCLUSIONS

These analyses indicate that the Kavalier ware is a calcium, potassium, sodium silicate with only inappreciable amounts of other elements. The Macbeth Evans Glass Co. ware is a sodium, zinc, magnesium borosilicate containing some antimony. The Pyrex ware is a very acid sodium, aluminium borosilicate containing some arsenic. The Jena ware is a zinc, sodium, aluminium borosilicate. The Nonsol ware is a sodium, zinc, magnesium, aluminium borosilicate with very little arsenic but some antimony. The Fry ware is a sodium, zinc, magnesium, calcium, aluminium borosilicate. The Libbey ware is a sodium, aluminium, lead borosilicate containing some arsenic.

The analyses may be of help when extreme care must be taken to avoid introducing small amounts of certain substances from the glass used. For example, the Kavalier is the only ware free from boron, and the Kavalier, Pyrex, and Libbey are the only wares free from zinc. No conclusions as to relative values of the different wares for general laboratory use can be drawn from these analyses.

IV. TESTS

1. PHYSICAL TESTS

(*a*) METHODS.—*Coefficient of Expansion.*[16]—The absolute coefficient of linear expansion was determined on pieces cut from the side of a Kavalier beaker, and on cylinders cut from the necks of flasks of all the other brands, by the Fizeau-Pulfrich interference method [17] for the temperature interval 10° to 55° C. Observations were made with both rising and falling temperatures, the average figures being reported.

Refractive Index.[18]—The refractive indices for monochromatic light (n_D) and dispersion ($n_F - n_C$) were measured on pieces from all the kinds of glass, using a Pulfrich refractometer.

Strain.[19]—Plane polarized light was obtained by reflection from a plane glass plate and changed to circularly polarized light by passing it through a quarter-wave plate of mica. The sample to be examined was then placed in the path of the circularly polarized light. If the sample was strained, the circularly polarized light was divided into two beams at right angles, which were then

[16] Determination made by C. G. Peters, Bureau of Standards.
[17] Fizeau, Ann. de Chim. et de Phys., 4, (2), p. 146; Pulfrich, Zeit. für Instrumentenk., September, 1898.
[18] Determinations made by H. I. Shultz, Bureau of Standards.
[19] Tests made by H. I. Shultz, Bureau of Standards.

changed to plane polarized light by a small quarter-wave plate. Behind this quarter-wave plate was the analyzing prism, with which interference between the two portions of light was viewed.[20] With no strain no interference is visible. A slight amount of strain shows up as a grayish color, which becomes dark brown (almost black) with increasing strain. If the strain is very strong, interference colors from blue to red appear. A grayish color is called a slight strain, somewhat brownish moderate, and a dark color, approaching blue, strong.

The quarter-wave plate nearest the eye, since it is close to the eye and does not diminish the field, is small (1 cm in diameter). The quarter-wave plate on the other side of the specimen is about 10 by 13 cm, enabling the operator to observe a large portion of the specimen at once.

Evaporation Test.—Unweighed beakers containing 100 cc of a 10 per cent solution of sodium chloride were heated on a steam bath with full head of steam until the residue was completely dry. The beakers with the residue of dry salt were then heated overnight on a plate heated by steam at about 120 pounds' pressure. After cooling they were washed and dried by heating at 100° C. for two hours and the bottoms carefully examined for minute cracks. This treatment was repeated 12 times, four beakers of each kind of glass being subjected to this test.

Heat-Shock Tests.—Vessels containing 200 cc of boiling water were plunged into ice water.

Vessels containing 200 cc of ice water (0° C to 4° C) were supported on nichrome triangles and heated to boiling as rapidly as possible by direct application of the flame of a burner of Meker type 3 cm in diameter at the top of the burner. The flame was 20 cm high and the top of the burner 2½ cm below the bottom of the beaker or flask. Beakers were covered with watch glasses during the heating, but the flasks were uncovered.

Vessels containing 200 cc of melted paraffin were heated on a hot plate until a thermometer in the paraffin indicated a temperature of about 160° C, then removed from the plate and the paraffin stirred with the thermometer until the temperature fell to 150° C. They were then plunged into ice water.

Vessels containing 200 cc of melted paraffin were heated to about 215° C, removed from the hot plate, the paraffin stirred

[20] Coker, Engineering, 91, pp. 1–4; 1911.

with the thermometer until the temperature fell to 200° C, and the vessels plunged into ice water.

Drop Test.—Beakers were dropped bottom down on a board 1½ inches thick resting on a table with a wooden top 1 inch thick, from heights varying by 5 inches until the piece tested broke or stood a fall of 45 inches.

(*b*) RESULTS.—Table 3 gives the coefficient of linear expansion, refractive index, and dispersion of the ware tested.

TABLE 3.—Linear Expansion and Optical Properties

Glass	Coefficient of linear expansion per degree centigrade from 10 to 55	Refractive index n_D	Dispersion $n_F - n_C$
Kavalier	0.00000759	1.5077	0.00841
M. E. G. Co	.00000600	1.5090	.00878
Pyrex	.00000334	1.4754	.00738
Jena (flask)	.00000479	1.5079	.00840
Jena (beaker)		1.5069	.00840
Nonsol	.00000640	1.5142	.00822
Fry	.00000596	1.5114	.00826
Libbey	.00000506	1.4963	.00789

Table 4 gives a summary of the observations on strain.

TABLE 4.—Strain Tests

[Number of pieces showing various degrees of strain]

Ware	Degree of strain	Beakers					Flasks					
		Entire beaker	Bottom	Sides	Rim	Lip	Entire flask	Bulb	Neck	Rim	Bottom	Junction of neck and bulb
Kavalier (48 beakers and no flasks tested)	None	3	3	5	16	8	.....	.....	.....	.....	.....	....
	Slight	37	4	39	25	34	.....	.....	.....	.....	.....	....
	Medium	5	0	4	4	4	.....	.....	.....	.....	.....	....
	Strong	3	0	0	3	2	.....	.....	.....	.....	.....	....
M. E. G. Co. (46 beakers and 48 flasks tested)	None	3	46	33	28	4	0	48	0	48	24	48
	Slight	39	0	11	17	40	48	0	48	0	24	0
	Medium	3	0	1	1	2	0	0	0	0	0	0
	Strong	1	0	1	0	0	0	0	0	0	0	0
Pyrex (48 beakers and 41 flasks tested)	None	2	2	23	23	46	0	36	0	0	34	41
	Slight	19	15	19	18	1	15	4	14	15	7	0
	Medium	21	26	3	7	1	16	1	17	16	1	0
	Strong	6	5	3	0	0	10	0	10	10	0	0
Jena (48 beakers and 33 flasks tested)	None	11	28	18	45	33	5	17	14	31	24	28
	Slight	27	15	19	3	9	19	12	10	1	4	2
	Medium	9	4	11	0	6	5	2	5	0	3	1
	Strong	1	1	0	0	0	4	2	4	1	2	2
Nonsol (48 beakers and 35 flasks tested)	None	21	37	42	32	33	12	21	18	32	33	35
	Slight	27	11	6	16	15	18	14	12	2	2	0
	Medium	0	0	0	0	0	4	0	4	1	0	0
	Strong	0	0	0	0	0	1	0	1	0	0	0
Fry (48 beakers and 48 flasks tested)	None	10	33	43	40	20	1	48	1	20	39	48
	Slight	28	7	3	8	21	36	0	37	25	4	0
	Medium	6	5	1	0	3	9	0	8	3	3	0
	Strong	4	3	1	0	4	2	0	2	0	2	0
Libbey (43 beakers and 49 flasks tested)	None	13	41	30	39	19	0	34	5	17	26	49
	Slight	11	1	2	0	9	3	0	6	0	3	0
	Medium	9	0	5	0	5	10	1	12	2	2	0
	Strong	10	1	6	4	10	36	14	26	30	18	0

All the pieces tested stood the evaporation test without developing cracks.

Table 5 shows the results of all heat shock and drop tests, the results of the strain tests on the individual pieces subjected to these tests being included in this table.

TABLE 5.—Heat-Shock Tests and Drop Test

Ware	Water at 4° heated to boiling over direct flame				Boiled water and plunged into ice water				150° paraffin test			
	Beakers		Flasks		Beakers		Flasks		Beakers		Flasks	
	Strain in piece tested	Result of test	Strain in piece tested	Result of test	Strain in piece tested	Result of test	Strain in piece tested	Result of test	Strain in piece tested	Result of test	Strain in piece tested	Result of test
Kavalier	Slight	Uninjured			Slight	Uninjured			Slight	Cracked		
	Do	Cracked			Strong	do			Strong	Uninjured		
	Do	do										
	Do	do										
M. E. G. Co	Slight	Uninjured	Slight	Cracked	Medium	Uninjured	Slight	Uninjured	Slight	Uninjured	Slight	Uninjured
	Do	do	do	Uninjured	Slight	do	do	do	Medium	Cracked	do	Cracked
			Do	Cracked							do	Uninjured
			Do	Uninjured								
Pyrex	Medium	Uninjured	Slight	Uninjured	Strong	Uninjured	Slight	Uninjured	Slight	Uninjured	Slight	Uninjured
	Do	do	do	do	Slight	do	do	do	Strong	do	do	Do.
Jena	Slight	Uninjured	Slight	Uninjured	Slight	Uninjured	Slight	Uninjured	Slight	Uninjured	Slight	Uninjured
	Strong	do	do	do	do	do	do	do	do	do	do	Do.
Nonsol	Slight	Uninjured	Medium	Uninjured	None	Uninjured	Medium	Uninjured	None	Uninjured	Medium	Uninjured
	None	do	Slight	do	Slight	do	Slight	do	Slight	do	Slight	Do.
Fry	Slight	Uninjured	Medium	Uninjured	Slight	Uninjured	Medium	Uninjured	Slight	Uninjured	Slight	Uninjured
	Do	do	Slight	do	do	do	Slight	do	None	do	Medium	Cracked
									Slight	do	Slight	Uninjured
									(?)	Cracked	Strong	Do.
Libbey	Slight	Uninjured	Slight	Uninjured	Slight	Uninjured	Slight	Uninjured	Slight	Uninjured	Slight	Uninjured
	Strong	do	Strong	do	Strong	do	Strong	do	Strong	do	Strong	Do.
									Do	do	Medium	Do.
									Do	do	do	Do.

TABLE 5.—Heat-Shock Tests and Drop Test—Continued.

Ware	200° paraffin test				Drop test, beakers only	
	Beakers		Flasks			
	Strain in piece tested	Result of test	Strain in piece tested	Result of test	Strain in piece tested	Result of test
Kavalier	Slight	Broke			Slight	Broke at 5 inches
	Do	do			do	Do.
	Do	do			do	Do.
	Strong	do			do	Do.
					Strong	Broke at 10 inches
					Slight	Do.
M. E. G. Co	Slight	Broke	Slight	Broke	Slight	Broke at 10 inches
	Do	do	do	do	do	Do.
	Do	do	do	do	do	Broke at 5 inches
	None	do			do	Broke at 10 inches
					Do	Broke at 5 inches
					Strong	Do.
Pyrex	Medium	Uninjured	Medium	Uninjured	Slight	Broke at 30 inches
	Do	do	Slight	do	do	Broke at 15 inches
	Strong	do	do	Cracked	Medium	Stood 25 inches and bounded to floor
	Medium	do	do	do	Strong	Did not break at 45 inches
			Do	Uninjured	do	Do.
					Slight	Broke at 25 inches
Jena	Slight	Broke	None	Broke	Medium	Broke at 10 inches
	Strong	do	Slight	do	Slight	Do.
	Slight	do	do	Uninjured	do	Do.
	Do	Uninjured	do	Broke	do	Broke at 5 inches
					Do	Do.
					Do	Broke at 20 inches
Nonsol	Slight	Uninjured	Strong	Broke	None	Broke at 15 inches
	None	do	Medium	do	do	Broke at 5 inches
	Do	do	Slight	do	do	Do.
	Slight	do	None	do	Slight	Broke at 15 inches
					Do	Broke at 10 inches
					Do	Broke at 5 inches

Fry	None	Broke	Slight	Broke	None	Broke at 20 inches
	Slight	do	Medium	do	Slight	Broke at 5 inches
	Do	do	Slight	do	do	Broke at 10 inches
	Do	do	Strong	do	do	Broke at 20 inches
					Medium	Broke at 10 inches
					Slight	Broke at 30 inches
Libbey	Strong	Uninjured	Strong	Broke	None	Broke at 20 inches (on bound)
	Slight	do	Medium	do	Strong	Broke at 10 inches
	Strong	do	do	do	Medium	Broke at 30 inches
	Do	do	Slight	do	Slight	Broke at 5 inches
					Medium	Broke at 30 inches
					Slight	Broke at 5 inches

(*c*) CONCLUSIONS.—The figures for coefficient of expansion are of interest in that they are all low as compared with plate, crown, and flint glasses, which are reported in Smithsonian Physical Tables (sixth edition), as ranging from 0.00000788 to 0.00000954. The figure for Pyrex glass is unusually low and is in very good agreement with the value, 0.0000032, given by Sullivan and Taylor.[21] The refractive indices and dispersion figures are not of any special interest except that the refractive index of Pyrex glass is very low. It was hoped that the tests for strain would prove useful in giving information as to resistance to changes in temperature and to mechanical shock, but study of Tables 4 and 5 shows that there is apparently no connection between the condition of strain and the resistance to changes in temperature and to mechanical shock. The evaporation test shows that all the ware is superior to several lots of unmarked ware reported[22] 12 years ago. Since none of the samples failed under this test it does not give information as to the relative values of the wares tested. The number of pieces available for the several heat-shock tests and for the drop test was too small to justify drawing any positive conclusions, since applying these tests to several hundred pieces of each kind of ware might give average results radically different from those obtained on the small number tested; but with this reservation, the tests indicate that the Kavalier and M. E. G. Co. wares are less resistant than Jena, Nonsol, and Fry wares, the Libbey ware somewhat more resistant, and the Pyrex ware distinctly more resistant.

2. CHEMICAL TESTS

(*a*) METHODS.—The chemical tests were designed to show the effect of ordinary laboratory operations on the various kinds of glassware tested. The effect of the various treatments was judged in each case by the loss in weight of the piece tested. All pieces to be tested were cleaned by washing with water, strong hydrochloric acid, distilled water, then filled completely with distilled water, and allowed to stand at room temperature for 24 hours, the water then being emptied, the vessels heated at the temperature of boiling water for 2 hours, allowed to stand at room temperature, protected from dust (but not in a desiccator), and weighed. All weighings were made against a tare piece of the same ware, which was cleaned in the manner described above and heated in the same oven as the test piece. The tare pieces

[21] J. Ind. & Eng. Chem., 7, p. 1064; 1915.

[22] J. Am. Chem. Soc., 28, p. 865; 1905.

were always placed in the oven and cooled at the same time and on the same table as the test pieces, but not otherwise subjected to any treatment after the first cleaning. Pieces which had received no treatment except the above-described cleaning were used for each test.

The losses in weight were determined by two observers, using different balances, different pieces of the wares, and different tare pieces. The pieces were sometimes heated in an electrically-heated drying oven and sometimes in a gas-heated oven. Repeated weighings of flasks over a period of 4 days without bringing the ware into contact with reagents, but heating a number of times in both types of ovens, showed that a single observer is liable to an error of about 1 mg in weighing, and as the errors with two observers may be in the opposite direction, duplication within 2 mg is all that can be expected.

In the water test on beakers 300 cc of distilled water was placed in each beaker, which was covered with a platinum dish and heated on a plate heated by steam at boiler pressure (100 to 120 pounds). Water was added from time to time to keep the volume approximately 300 cc. The beakers were removed from the hot plate each evening and allowed to stand at room temperature overnight. The test extended over about 72 hours, of which 24 hours was on the hot plate, and about 48 hours on the laboratory table. The beakers were then washed with water, hydrochloric acid, and again distilled water, dried, and weighed as described above. With flasks 250 cc of water was used throughout; this was allowed to stand for 17 hours at room temperature and then boiled uncovered on a gas-heated hot plate for 5 hours, hot water being added from time to time to keep the volume approximately 250 cc. The vessels were then cleaned, dried, and weighed as above.

With sodium carbonate, potassium carbonate, sodium hydroxide, potassium hydroxide, and sodium phosphate, 100 cc of half-normal solutions were boiled gently for 20 minutes in the covered test vessels. The vessels were then washed with water, hydrochloric acid, and again with water, dried, and weighed as in the preliminary treatment. In the case of beakers, but not with the flasks, after determining the loss by the first treatment another 100 cc of the reagent solution was boiled for 20 minutes, then evaporated to dryness on a plate heated by steam (at 100 to 120 pounds pressure). The beakers were then cleaned, dried, and weighed as above.

With ammonia, 75 cc of strong ammonia (0.9 specific gravity) was placed in the test vessel, which was covered with platinum, and allowed to stand at room temperature for 24 hours. Then 150 cc of distilled water was added, heated to boiling and boiled gently for 30 minutes. The liquid was poured out and the vessel washed with water, hydrochloric acid, and again with water, dried, and weighed as before.

With ammonium sulphide and ammonium chloride, 100 cc of 2N ammonium sulphide and 50 cc 2N ammonium chloride were placed in the test pieces, covered with platinum, allowed to stand at room temperature for 24 hours, then boiled gently for 30 minutes. The liquid was then poured out, the vessel washed with water, a mixture of hydrochloric acid and bromine water, again with water, dried, and weighed as before.

The acid treatment was conducted as follows: 25 cc of a solution containing 4 g sodium chloride and 4 g sodium nitrate per 100 cc was placed in the test pieces. Then 50 cc of sulphuric acid (1.5 specific gravity) was added, the vessel covered and heated to boiling on a gas-heated hot plate. The cover was then removed and heating continued for an hour after fumes of SO_3 appeared. The test piece was allowed to cool, about 100 cc of water added, the liquid poured out, the vessel washed with water, hydrochloric acid, and again with water. It was then dried, cooled, and weighed as before.

(*b*) Results.—Results are shown in Figs. 4, 5, 6, and 7, in which the letters *K*, *M*, *P*, *J*, *N*, *F*, and *L* indicate Kavalier, M. E. G. Co., Pyrex, Jena, Nonsol, Fry, and Libbey, respectively. In these figures individual accepted determinations are shown by dots, determinations which are believed in error and therefore omitted from the averages by circles. The length of the rectangles indicates averages of the accepted values.

(*c*) Conclusions.—In general, it may be observed that where the losses in a given test are small, say, less than 15 mg, the duplicate determinations agree fairly well. The results, however, vary widely when the losses are large.

Considering the tests separately we find that with water the Kavalier ware is unsatisfactory. All the rest show good resistance, and while the determinations show slight superiority of the Pyrex and Libbey glasses over the M. E. G. Co., Jena, Nonsol, and Fry, the differences are so small and the resistance of all of these glasses is so good that it may be concluded that all of the ware examined except the Kavalier is satisfactory in this respect.

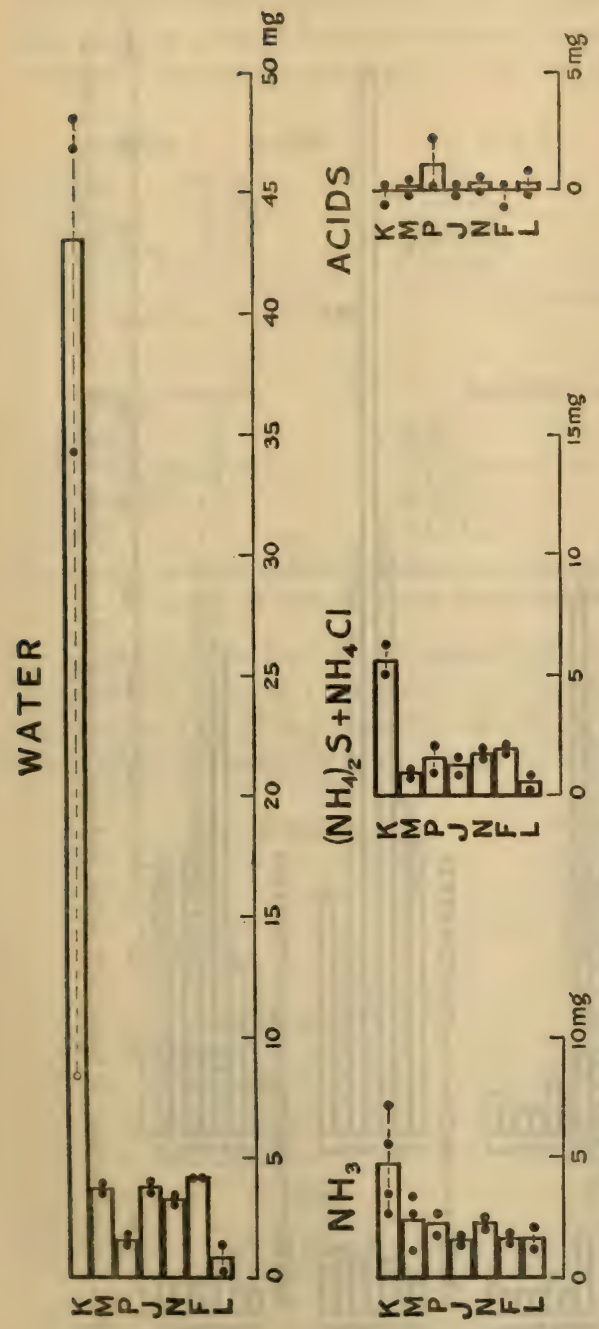
WATER
0 5 10 15 20 25 30 35 40 45 50 mg
K M P J N F L
NH3
0 5 10mg
K M P J N F L
(NH4)2S+NH4Cl
0 5 10 15mg
K M P J N F L
ACIDS
0 5mg
K M P J N F L
BOILED ← Na2HPO4 → EVAPORATED
K M P J N F L
K M P J N F L

FIG. 4.—*Loss in weight of beakers with water, ammonia, ammonium sulphide and chloride, acids, and sodium phosphate solutions.*

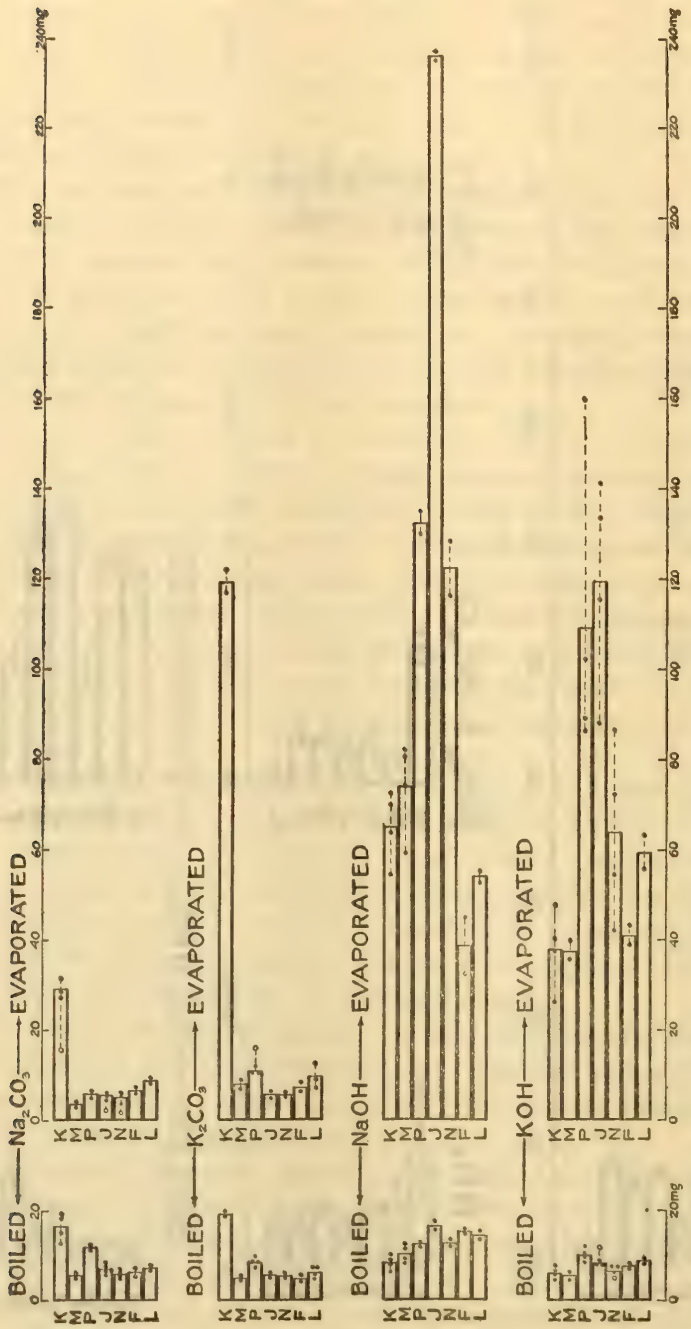

FIG. 5.—*Loss in weight of beakers with sodium carbonate, potassium carbonate, sodium hydroxide, and potassium hydroxide solutions.*

With acids all of the glasses examined show excellent resistance. The acid tests confirm the conclusion of practically all observers that glass in general is more resistant to acid solutions than to alkaline solutions or pure water. The test with boiling alkaline

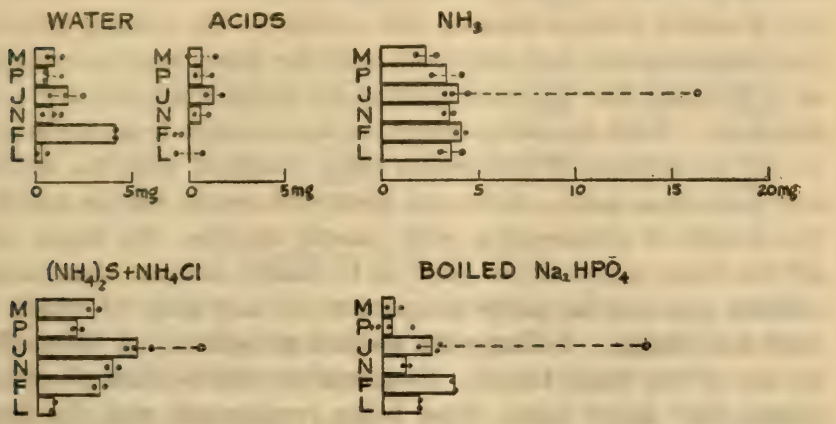

FIG. 6.—*Loss in weight of flasks with water, acids, ammonia, ammonium sulphide and chloride, and sodium phosphate solutions.*

carbonates shows that the Kavalier ware is the least resistant, showing losses above 15 mg; that the Pyrex is intermediate with losses from 8 to 12 mg; and that the M. E. G. Co., Jena, Nonsol, Fry, and Libbey are very nearly equal with losses approximately 5

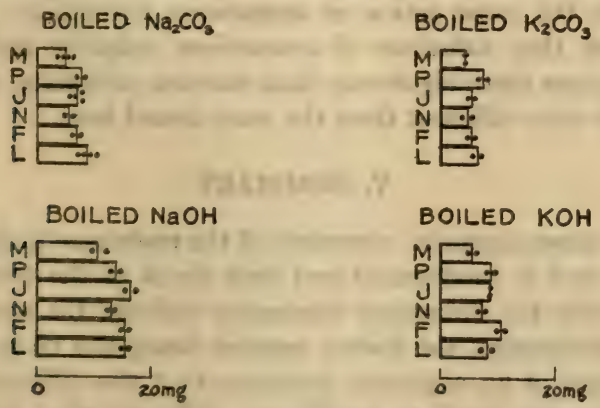

FIG. 7.—*Loss in weight of flasks with sodium carbonate, potassium carbonate, sodium hydroxide, and potassium hydroxide solutions.*

to 7 mg. There is no appreciable difference in the action of sodium and potassium carbonates. With boiling caustic alkalies the Kavalier and M. E. G. Co. wares seem to be slightly more resistant than the others; the differences are not, however, very

great. It may also be noted that sodium hydroxide appears to be somewhat more active than potassium hydroxide. With the evaporation tests it must be remembered that these tests were made on the same beakers that had been used for the determination of the loss on boiling. On evaporation with carbonated alkali the Kavalier beakers showed less action by the sodium than by the potassium salt, but with both salts the losses were so excessive as to indicate that Kavalier ware is not suitable for use with such solutions. With the other wares the losses range from about 5 to 12 mg, no appreciable differences being observed with the sodium and potassium salts. Although great differences will be noted in the results of evaporation with caustic alkalies, the losses with all the wares tested are so great as to clearly indicate that caustic alkalies can not be safely evaporated in any glass of which we have knowledge. Boiling with sodium phosphate has little effect on any of the wares tested. Evaporation with sodium phosphate causes only slight losses, these being comparable with the losses on evaporation with carbonated alkali, except with the Kavalier ware. This on both tests with sodium phosphate compared favorably with the other wares in contrast with the poor resistance to carbonated alkali. The tests with ammonia and with a mixture of ammonium sulphide and chloride show that ammonium compounds have less action than fixed alkali carbonates, and also show that the mixture of ammonium sulphide and chloride has practically the same action as ammonium hydroxide. Cowper,[23] who noted that solutions of ammonium sulphide and chloride attacked glass more vigorously than sodium carbonate, must have used glass very different from the ware tested here.

V. SUMMARY

Table 6 gives a general summary of the resistance to the various solutions and to mechanical and heat shock of the wares tested. In this table the numerical exponents indicate the minor differences in resistance, the lowest number being the most resistant. The absence of an exponent indicates that the differences in resistance are too small to justify any differentiation between the wares graded in the same group. In the rating of resistance to caustic alkalies the boiling tests only have been considered.

[23] J. Chem. Soc., 41, p. 254; 1882.

TABLE 6.—General Summary of Tests

Ware	Resistance to—						
	Water	Mineral acids	Carbonated alkalies	Caustic alkalies	Ammonia and ammonium salts	Heat shock	Mechanical shock
Kavalier	Poor	Good	Poor	Good [2]	Good [2]	Poor	Poor.
M. E. G. Co	Good [3]	Good	Good [1]	Good [1]	Good	Poor	Poor.
Pyrex	Good [2]	Good	Good [3]	Fair	Good	Good [1]	Good.[a]
Jena	Good [4]	Good	Good [2]	Fair	Good	Good [3]	Fair.
Nonsol	Good [3]	Good	Good [1]	Fair	Good	Good [2]	Fair.
Fry	Good [4]	Good	Good [3]	Fair	Good	Poor	Good.
Libbey	Good [1]	Good	Good [3]	Fair	Good	Good [2]	Good.

[a] Far superior to any of the other wares.

These results indicate that all the American-made wares tested are superior to Kavalier and equal or superior to Jena ware for general chemical laboratory use.

WASHINGTON, October 1, 1917.

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S. W. STRATTON, DIRECTOR

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GROUND CONNECTIONS FOR ELECTRICAL SYSTEMS

BY

O. S. PETERS, Assistant Physicist

Bureau of Standards

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By O. S. Peters

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I. INTRODUCTION

Ground connections have come in recent years to play an increasingly important part in electrical systems of almost every kind. One of their chief functions is that of protecting persons against electrical dangers. Where depended upon for this purpose, they should be carefully made, because if they are poorly made, or inadequate for the purpose for which they are intended, loss of life or serious personal injury may result. Nevertheless, surprisingly little has been done to make generally known the

information available concerning ground connections in common use, and research on the subject has been limited. It is true, of course, that the desirability of grounding has been extensively discussed in its different phases; and although there still is some discussion as to the extent to which grounding should be carried, there is now fair agreement as to the parts of electrical systems which can be operated most advantageously when connected to earth.

With regard to the performance of ground connections under operating conditions, and the physical characteristics which they must possess to meet the requirements placed upon them, comparatively little has been written. As a result, information which is important to persons directly engaged in the safeguarding of life and property from electrical dangers by the use of ground connections is not readily obtainable. The consequences of this difficulty in obtaining information are evident in a more or less general lack of thoroughness and uniformity in the practice of grounding, and accidents due to inadequate ground connections not infrequently occur.

The object of this paper is to present the information now available concerning ground connections and their uses, and to supplement this information with new experimental evidence which, among other things, shows the necessity for basing specifications for ground connections upon their physical characteristics rather than upon arbitrary methods of construction as has been the custom to a large extent in the past. Considerable space is devoted to discussing the manner in which danger arises from ungrounded electrical systems, and also the desirability of grounding to avert such danger. The subject is taken up with special reference to the grounding rules of the National Electrical Safety Code[1] under the following main topics: (1) Resistance of ground connections; (2) their uses and service conditions; (3) different forms of ground connections and the electrical characteristics of each; (4) mechanical construction; (5) inspection and testing; (6) fire hazard and interference with service; (7) costs; (8) bases for specifications; and (9) field measurements of the resistance of ground connections.

With the object outlined above in view, a careful survey of the literature on grounding and ground connections has been made; considerable experimental work has been done in the laboratory and in the field, and correspondence and conferences had with

[1] See Appendix II.

representatives of corporations engaged in the generation and distribution of electrical energy. The results of this study will be taken up after referring to some of the terms used in the following discussion, and also stating briefly the purpose of a ground connection.

1. TERMINOLOGY

The terms "ground," "permanent ground," "ground connection," and, in a few cases, "earth connection," as herein used, refer to electrical connections intentionally made between electrical circuits, or conducting bodies in close proximity to electrical circuits, and metallic bodies embedded in the earth, such as water pipes, plates, or driven pipes.

Every connection between electrical circuits and ground or near-by conducting bodies made, not by design, but by accident, as by the breaking of wires or failure of insulation, is referred to as an "accidental ground."

2. PURPOSE OF GROUND CONNECTIONS

The purpose of a ground connection is to keep some point in an electrical circuit, or some conducting body, at, or as near as practicable to, the potential of the ground in order either that safety to life and property be secured, or that there be increased convenience and continuity of service in the operation of electrical systems. "Ground" here may mean either the soil itself, or conducting bodies in contact with it or extending into it. Examples of the latter are steel building frames, steel poles, and water and gas pipes, and fixtures in buildings. In many instances it is necessary that there be a considerable flow of current through the ground connection in order to prevent the potential of an electrical circuit or a conducting body from rising to a dangerously high value above that of the ground. The soil offers more or less resistance to this current flow, and this resistance determines in large measure the effectiveness of the ground in protecting against high voltage. The nature of the resistance of a ground connection will therefore first be considered.

II. RESISTANCE OF GROUND CONNECTIONS

If two electrodes, such as pieces of iron pipe several feet in length or plates or other bodies of metal, are embedded in earth at a distance from each other and have impressed upon them a steady alternating difference of potential, a current will flow between

them, the value of which depends upon the electrical resistance offered by the soil. This resistance is made evident by the liberation of heat when current is flowing, and because of its effects on the performance of ground connections in service, it is of interest to consider the factors which affect it and its distribution in the region surrounding the metallic bodies.

1. CONTACT RESISTANCE BETWEEN METAL AND EARTH

One factor which has in many instances been considered as contributing to the resistance of a ground connection is that of contact resistance between metal and earth. In order to obtain an idea of the magnitude of this contact resistance, some measurements were made at the Bureau of Standards. For the purpose of these measurements, several samples of earth were used, each of which was thoroughly mixed before testing in order to make the resistivity as uniform as possible throughout. Tests were then made by placing different quantities of each sample in a cylindrical vessel having an iron bottom and glass-lined sides, compressing it by forcing an iron piston down upon it, and measuring the electrical resistance between the piston and the metallic bottom, using alternating current at 60 cycles per second. Measurements made at the same unit pressure, and with the cylinder filled to depths ranging from 2 to 9 cm., showed the same specific resistance for each depth; that is, within the limits of accuracy of the measurements, or about 2 per cent. If contact resistance were present, an apparently greater specific resistance would have been shown with the smaller depths of earth in the cylinder than with the greater depths, but this was found not to be the case; consequently, it may be concluded that the effects of contact resistance between clean iron and earth when firmly pressed together are negligible, at least as far as practical purposes are concerned. The contact resistance between earth and metals other than iron has not been determined, but it seems reasonable to infer that for those metals commonly used for ground connections, viz, copper and galvanized iron, the latter of which presents a zinc-coated surface, the same results would be obtained.

In practice, however, clean metal is not always found. The electrodes used in making ground connections may be covered with substances such as rust, paint, or grease, and these in some instances are not unlikely to form a more or less insulating layer between metal and soil. Rust, of course, is the one most commonly

found, but in none of the experiments thus far conducted by this Bureau upon the corrosion of iron in soil has it developed that a layer of rust appreciably increases the resistance to flow of current away from the metal. From the results of these tests, and also from the fact that rust layers formed in soil are permeable to soil water and consist of particles of iron oxide of no greater insulating qualities than the particles forming the soil itself, it may be safely stated that rust is of no effect in increasing the resistance of a ground connection. Paint or grease, however, should be removed before the metal is buried.

A case in which an apparent contact resistance between metal and earth may arise is where a ground connection is required to carry direct current. This may be important, especially in making resistance measurements at low voltage, and the effects of direct current, as compared with these of alternating current, should be given careful consideration. For when direct current is used in making resistance measurements, electrolysis takes place at the surface of the electrode. By this means gas is liberated which soon forms a high-resistance layer between metal and earth, and in conjunction with other factors, makes a very marked difference (generally an increase) in the apparent resistance as compared with the resistance obtained with alternating current. The magnitude of this difference in resistance depends upon the polarity of the electrode, upon the rate of current flow, upon the rate at which gas is able to diffuse from the surface, and also upon the counter electromotive force of polarization. It may amount to as much as 20 or 25 per cent.

On the other hand, when alternating current is used, the resultant electrolysis is very small. The rate at which reversals of current would have to take place in order entirely to prevent electrolysis under all conditions has not been determined, but some experiments have been conducted recently at the Bureau of Standards which indicate the magnitude of the resultant electrolysis with current at 60 cycles, or 120 reversals per second. These experiments were made on iron and lead in moist clay. It was found from tests lasting through several weeks that the amount of iron or lead lost with a certain number of ampere-hours of alternating current was a fraction of 1 per cent of the loss with an equal number of ampere-hours of direct current.[2] There are, of course, other products of electrolysis than dissolved

[2] Technologic Paper No. 72 of the Bureau of Standards.

metal which would affect measurements of the resistance of ground connections, but it seems that it may safely be inferred from the results just mentioned that they are comparable in amount with the dissolved metal and are, therefore, of negligible effect as far as measurements in practice are concerned.

From the foregoing discussion, it appears, then, that if contact resistance is present in a ground connection, it is something which is not inherent in the contact between clean metal and packed earth, or even between rusty metal and packed earth. As indicated above, it is most likely to be due to an impervious nonconducting coating on the surface of the metal, such as paint, grease, or gas formed by chemical action or electrolysis. Furthermore, in the measurement of resistance of ground connections with direct current, the contact conditions between metal and soil are disturbed to an appreciable extent by the action of the current, whereas with alternating current at 60 cycles per second, this disturbance is inappreciable. Alternating current is, therefore, preferable for making measurements of the resistance of ground connections.

2. TOTAL RESISTANCE OF A GROUND CONNECTION

Having considered the matter of contact resistance between metal and earth, attention may now be turned toward what may be called the actual or total resistance of a ground connection. This must be considered in every case. It consists of three parts, viz, (1) a part contributed by the ground wire or other conductor, which serves to make an electrical connection between the buried electrode and the electric circuit or metallic body which the ground connection is designed to serve; (2) a part contributed by the buried electrode itself; (3) a part contributed by the soil. The part contributed by the ground conductor may properly be taken as a part of the total resistance because, as far as the effect on the electric circuit or metallic body mentioned above is concerned, it makes no difference whether the resistance is in the conductor or the soil. Its importance is not great, however, unless an exceedingly long ground wire is used, or connection is made to a long service pipe in making water-pipe grounds.

The resistance of the buried electrode enters because of the fact that the current flows into the electrode at a point, that is, where the ground conductor is attached, and to reach the surface must pass through the metal. Each element of current, there-

fore, traverses a path of greater or less length depending upon the distance between the point where the ground conductor is attached and the point where the particular element of current passes into the soil. The part of the total resistance contributed by the buried metal is the combined resistance of all these paths in parallel. The resistivity of metals, however, is exceedingly small in comparison with that of soils, which has been found by measurement to range from a few hundreds to many thousands of ohms[3] for a centimeter cube.[3] Hence, for electrodes of limited extent, the part of the total resistance contributed by the metal can be neglected and consideration confined to that due to the soil surrounding it. For electrodes of great length and comparatively small cross section, however, this may not be the case. Where water pipes are used, for instance, a large part of the elements of current must traverse the pipe over considerable distances before passing into the ground, and since these paths are of great length in comparison with their cross section, they may contribute very appreciably to the total resistance, especially if the pipe contains high-resistance joints. Lead joints, under ordinary circumstances, of course, are of such low resistance that their effects are of little consequence, but cement or "leadite" joints are of high resistance, and where these are used they may so contribute to the total resistance of a water-pipe ground connection as seriously to impair its effectiveness. The resistance of water-pipe grounds is considered again in Section IV, 5 (*a*).

The part of the total resistance contributed by the soil is the most important in nearly all cases. When current flows away from the electrode, each element of current traverses a path of variable cross section to its destination, which in practice is always another electrode at some distance away. The resistance offered by the soil, then, is the combined resistance of all the paths of the current elements in parallel, and since the resistivity of soil, as already pointed out, is high, this resistance will be high unless the electrode is very large and the comparative number of paths, therefore, very great. It should be mentioned that where current flows from one electrode to another, the resistance, as just set forth, is due to the soil surrounding two electrodes which may be said to be in series. To obtain the resistance to flow of current away from a single electrode, current may be made to flow from it to an electrode of such great extent that its resistance could be

[3] Technologic Paper No. 26 of the Bureau of Standards.

considered negligible. If two electrodes are placed at a distance from each other equal to several times their greatest dimension, the resistance to flow of current from one to the other is practically the sum of the resistances of each of the two grounds, a fact which is very useful in making resistance measurements. It is of interest to point out briefly the manner in which the resistance of the soil is distributed, especially about buried electrodes of limited extent.

3. DISTRIBUTION OF RESISTANCE IN THE EARTH ABOUT A METALLIC BODY

As a concrete example it is convenient to take a hemispherical electrode which may be supposed to be embedded in earth of uniform resistivity with its convex surface down and its plane surface flush with the surface of the ground. If very thin shells of uniform thickness are marked off concentrically with such a hemisphere, their mean areas will vary directly as the squares of their radii, and hence their resistances will vary inversely as the squares of their radii. Any part of the total resistance to flow of current away from such an electrode can be exactly stated by taking the sum of the resistances of the shells from the surface of the hemisphere to the desired distance. This inverse-square law, which holds exactly for a hemispherically shaped electrode, may also be considered as a rough approximation to the conditions as to distribution of resistance about any small electrode, such as a driven pipe; that is, a large part of the total resistance is found near by. It should be added that if the soil, instead of being of uniform resistivity as assumed above were variable, the foregoing simple case would not hold; the distribution of resistance would be more complex. An example is given later in which a quantity of salt is placed around a driven pipe in order to reduce the resistivity of the adjacent soil.

The practical importance of the character of the distribution of resistance about an electrode buried in the earth appears in its effect on the potential gradient in the vicinity of the electrode when heavy current is passing from it. Actual measurements, the results of which will be given later in this paper, show that in the case of driven pipes about 90 per cent of the total resistance is generally encountered in the first 6 to 10 feet; hence, the potential gradients on the earth's surface near the pipe may be high enough in the event of heavy current flow to cause a drop of potential between the pipe and points within reaching distance of it great enough to be dangerous to human life. This matter is discussed in detail in Section IV, 10.

4. FORMULA FOR THE RESISTANCE OF A GROUND CONNECTION

The simple physical idea of the distribution and value of the resistance of a ground connection which has just been given, serves very well for the purpose of illustration. But for working up certain kinds of experimental data, and also for showing the most advantageous way in which to make ground connections, it is desirable to go a step further and express the value of the resistance in terms of the resistivity of the soil and the dimensions and position of the metallic body. A mathematical formula which fulfills these conditions is readily derived and is given in many textbooks on electricity and magnetism. Its common form is as follows: $R=\frac{\rho}{2\pi C}$, where R is the resistance to flow of current away from the electrode forming the ground connection; ρ, the resistivity of the soil; and C, the combined electrostatic capacity in free space of the electrode and its image above the surface of the ground.[4] The value of C, it may be added, is a constant for any given shape and arrangement of an electrode.

From this formula, it appears that the resistance of a ground connection of any form can be calculated if the resistivity of the soil is known, but in practice difficulties are encountered which limit the use of the method very materially. The chief difficulty is that of obtaining convenient means for expressing the value of C, and this confines the use of the formula to a few simple cases. The resistivity of most soils is also far from uniform, and this presents another difficulty. The principal use of the formula in experimental work is that of drawing smooth curves from the results of observations on driven pipes, which, on account of the nature of the soil in most localities, are bound to be irregular. In this case the value of the electrostatic capacity of the pipe and its image in free space can be approximated by considering it an ellipsoid of revolution. Approximations which are very useful can also be made for other forms of electrodes such as long metal strips or wires.

In addition to serving to a certain extent as the basis of a method for working up observations, the formula given above also serves another purpose, which is, perhaps, still more important, and that is to show that the manner in which buried metal must be distributed in order to obtain the best results—that is, the

[4] For a derivation of this formula and a short discussion of electrical images as applied to this case, see Appendix III.

least resistance for a given amount of material—is also the manner in which it must be distributed to give the greatest value of C. This is a fact which can not be too strongly emphasized, inasmuch as there are recommendations in existence concerning the installation of ground connections in which area of plate or other electrode seems to be considered the most important matter and no thought given to distribution of metal. If due regard is given to this, much better results can be obtained in many cases for a given amount of material and labor, than if it is neglected. As an illustration, there is the matter of laying a wire in a stream bed to form a ground connection. Instead of coiling the wire, it should be strung out to its greatest length, because in this position the value of C is greatest, and hence, the value of R is the least. The importance of having a low value for R appears from a consideration of the uses found for ground connections in practice and the conditions under which they must operate.

III. USES AND SERVICE CONDITIONS OF GROUND CONNECTIONS

There are great differences in the service conditions imposed upon ground connections in the different practical cases involving their uses, and for that reason it is desirable to consider each case separately. The most important kinds of electrical circuits and apparatus or machinery with which ground connections are used, are the following: (1) Low-voltage,[5] alternating-current circuits; (2) direct-current distribution systems; (3) detectors of accidental grounds; (4) frames of electrical machines; (5) metallic bodies near or inclosing electrical circuits; (6) high-voltage transmission and distribution systems; (7) electrical systems under construction or repair; (8) lightning arresters and overhead ground wires; (9) lightning rods; (10) meter circuits. Ground connections are also used in signaling circuits, and in a number of ways for testing purposes. In the following discussion special emphasis is given to cases involving life hazard, for here the conditions to be met by the ground connection are more rigorous than where simply property hazard or convenience of operation and continuity of service are concerned.

[5] The term "low voltage," as here used, refers to circuits of the voltages commonly used for distribution within buildings to electrical utilization installations, generally 750 volts or less, while "high voltage" refers to circuits of the voltages commonly used for transmission and distribution in overhead and underground lines, except those directly connected to electrical utilization installations, generally over 750 volts.

1. LOW-VOLTAGE, ALTERNATING-CURRENT CIRCUITS

Low-voltage, alternating-current circuits are grounded primarily for the purpose of averting a life hazard which is due to their proximity to high-voltage circuits in transformer windings, on pole lines, in manholes, and other places where, because of lack of space, or for other reasons, it is necessary to place such circuits near each other. The actual danger arises from the entrance of current and voltage from the high-voltage circuit upon the low-voltage circuit, either through a leak in insulation between transformer windings, or through a contact or connection accidentally formed between wires, thus causing a rise of potential against ground of the low-voltage circuit which may be of a dangerous magnitude unless provision is made against it. Leaks in transformer insulation appear to have been at one time the most prevalent cause of this dangerous condition, but in recent years improvements in insulation and protection by lightning arresters have reduced the percentage of failures until the greatest number of cases of the entrance of high-voltage upon low-voltage circuits seems now to be due to accidental connections between wires. In an extreme case, if a leak or a contact between wires were formed and the low-voltage circuit was not permanently grounded through a low resistance, its potential against ground might reach practically the full voltage of the high-voltage circuit, as will be shown later.

The life hazard involved here is very serious, because people are continually coming in contact with electric-light fixtures and other apparatus and appliances connected to low-voltage circuits. It is, therefore, incumbent upon persons installing such circuits to make them as nearly absolutely safe as practicable. Much can be accomplished in this respect by grounding them. This method of protection was first suggested by Prof. Elihu Thomson in 1885, who patented it and dedicated the patent to the public.

(*a*) Causes of Leaks in Transformer Insulation.—As just stated, the danger from high-voltage circuits arises in some cases because of leaks through failures in transformer insulation. The chief causes of these failures are transient electrical disturbances set up in the high-voltage line by lightning or an accidental ground, which lead to abnormal stress upon the insulation between windings. Short circuits, switching, or sudden changes in load on the high-voltage line may also set up disturbances which may

cause failures. Further causes of failures are moisture in transformer oil, inferior oil, and heating due to overloading. Moreover, it may happen that in the construction of transformers, faulty insulating material is used which is too weak to withstand indefinitely even the ordinary working voltage of the system. But because of the rigorous tests to which transformers are usually subjected before being placed in service, a failure directly attributable to initially faulty insulation rarely occurs. In nearly all cases the factor of safety of insulation between windings in new transformers for voltages up to 3500 is between five and ten.[6] In spite of this high factor of safety, however, failures of transformer insulation induced by abnormal electrical stresses and other causes are of rather frequent occurrence.

In the past, much effort has been directed toward the development of apparatus to protect the transformers of high-voltage distribution systems against lightning and other high-frequency disturbances, and as a result, several kinds of lightning arresters, chiefly of the air-gap type, have been developed which give a fair degree of protection. In fact, against anything which is of such a character as to approach a steady electric stress, these arresters afford admirable protection, but against disturbances of high frequency the protection afforded is not so complete. The chief reason for this is found in the fact that in the air-gap arresters there is an appreciable time lag in the discharge, and in the event of an electrical disturbance suddenly striking the terminals of a transformer, its full effect can be imposed upon the insulation between the windings and between low-voltage circuit and ground, before the arrester has time to act and relieve the stress. Insulation is thus pierced a number of times in succession until, finally, an electrical connection is established between windings through charred insulation or cracked bushings. The number of transformers damaged through failure of insulation amounts each year to approximatedly 0.5 per cent of the total number in service, varying widely, of course, in different sections of the country.

(*b*) Causes of Accidental Contacts or Connections Between Wires.—The causes of accidental contacts or connections between wires may be designated, first, as those inherent in the lines themselves and, second, as those due to outside interference. Among the first may be mentioned the blowing together of wires by the wind. This is caused, in some cases, by the fact that wires

[6] Creighton, Trans. A. I. E. E., 26, Part II, pp. 1–51.

strung from the same cross arms are likely to have different periods of vibration when set in motion. At first, when the wind commences to blow, they may swing in unison; but soon one gains on the other until, if the span is long or the sag unusually great, they may touch or even wrap around each other. In other cases where conductors cross each other with too small a clearance, a wind blowing against the lower may raise it sufficiently to touch the upper. Wires may also stretch or break under ice loads and so fall or lie upon a circuit which happens to be below them. Conductors may also part by whipping in the wind and wearing off at insulators. In extreme cases ice or wind may carry down cross arms or even poles. The observance of proper requirements as to strength and clearances of lines (see National Electrical Safety Code, secs. 22, 23, etc.), will in large measure eliminate such accidents, although to avoid breakage entirely is very difficult, because an unusual combination of conditions occasionally arises, such as heavy ice storms and high winds of great velocity, against which it is so expensive as to be impracticable to prepare.

The causes of accidental connections between wires, which may be classed as due to outside interference, are numerous, but among the most important are kites and kite wires which become entangled with electrical circuits. These may easily connect a high-voltage circuit to a low-voltage circuit and constitute a menace to life unless care is taken to obviate the danger. Falling trees, limbs, or even twigs, may also cause trouble by breaking wires or causing them to sag, or when green by forming a high resistance connection from one wire to another. The use of insulators and wires as targets for firearms is another source of danger. As mentioned above, accidental contacts or connections between wires are, at present, probably the most prevalent cause of the entrance of high-voltage upon low-voltage circuits.

(*c*) Current and Potential Relations in Low-Voltage Circuits Due to Contact with High-Voltage Circuits.—When an electrical connection is established between high-voltage and low-voltage circuits, as just indicated, the low-voltage circuit becomes, in effect, a wire tapped into the high-voltage circuit at some point and extended to every place where there are lights and other appliances. Assuming for the moment that the high-voltage line is thoroughly insulated, except where the accidental

contact under consideration has occurred, it can readily be seen by referring to Fig. 1 that the potential of the low-voltage circuit against ground depends upon the location of the point of contact. If it is at the middle of a high-voltage transformer winding, this potential will be zero, because at any instant the potential of one wire of the high-voltage line will be as much above that of the middle of the winding as the potential of the other wire is below. As the point of contact is moved away from the middle, however, the potential of the low-voltage circuit against earth increases, reaching nearly 1100 volts at the end turn. The voltage at the end turn, of course, is the same as it would be if the point of contact were at any place on the line.

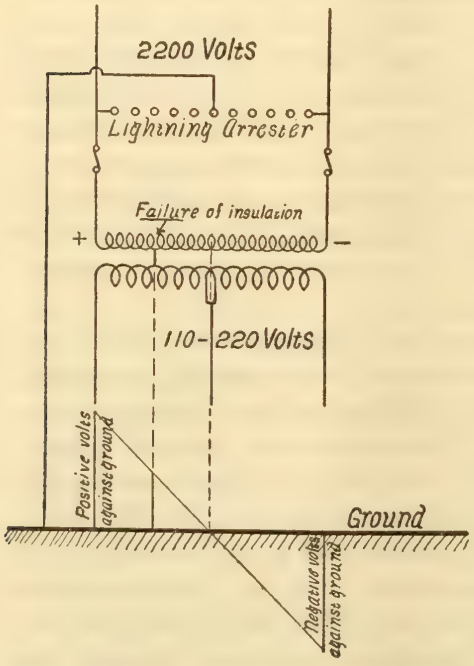


FIG. 1.—*Potential differences against ground of different points in a high-voltage winding*

If, now, an accidental ground is formed at any point on the low voltage circuit through a resistance R, current will flow into the condenser formed by the earth and the wires of the high-voltage line. The path of this current flow is represented in Fig. 2, the failure of insulation being supposed to have occurred on an end turn of the high-voltage winding, with the rest of the line thoroughly insulated. The total voltage across resistance and condenser in series is 2200, the position of the point of earth potential in the high-voltage winding depending upon the relative values of the resistance and capacity, and is, in general, no longer found at or near the middle point of the winding, as it was before the low-voltage circuit became grounded at R. It is obvious that if the body of a person were to take the place of the resistance R, the current flow might be sufficient to cause severe shock, or even death, with no other failure on the high-voltage line than the one under consideration. For this, however, the supply network would have to be several miles in length to afford

the necessary capacity between line and ground. With a 2200-volt supply system a mile in length, a current of approximately 10 milliamperes could be expected to flow, if the point of contact were at an end turn of the winding. Hence, as this current increases directly with the length of the line, a dangerous current flow would be obtained with a primary network extending over a distance of 10 or 12 miles.

Thus far it has been assumed that the high-voltage line is thoroughly insulated at every point except the one where the failure under consideration is supposed to have occurred. In actual practice, however, there is more or less leakage which combines with the capacity current and increases the total flow to such an extent that no high-voltage line can be said not to be dangerous when in contact with an ungrounded low-voltage circuit even though it is very short. The magnitude of the current flow which may take place from a 2200-volt distribution system to ground, due to capacity and leakage, is indicated by the fact that instances have been observed where a 5-ampere fuse was required to carry the current. Anything less would be blown. The lines in these cases, of course, were many miles in length and ungrounded except for the experimental ground on one phase containing the fuse.

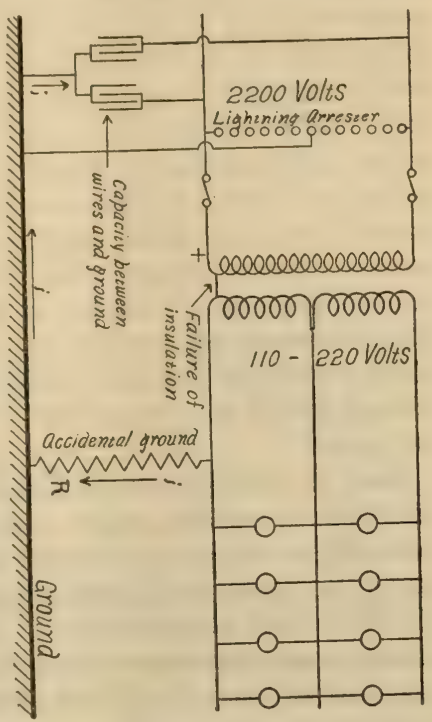


FIG. 2.—*Path of current flow with failure of insulation at end turn of high voltage winding and accidental ground on low-voltage circuit*

Aside from the leakage which may normally be expected on any extensive high-voltage system, it has been observed that there may be places where weak points in the insulation have developed, and in the event of a failure in a transformer, or a contact between wires, other failures are likely to occur elsewhere. If, therefore, in conjunction with a failure in a transformer, an accidental ground

of low resistance in comparison with the resistance R should form on the high-voltage line, the condenser represented in Fig. 2 would be, in effect, short-circuited, and a voltage would be impressed upon R which might range from zero to nearly full line voltage, depending upon the location of the points of failure in relation to each other. With the point of failure at an end turn of the transformer winding, or what amounts to the same thing, a contact between the wires of the high-voltage and the low-voltage circuits, and the accidental ground on the opposite wire of the line, 2200 volts would be impressed upon R and the accidental ground in series. This represents about the most serious condition with regard to potential difference between low-voltage circuit and ground that could arise. In this case the extent of the line would have no effect; a person occupying the position of R would receive the full line voltage, minus, of course, the drop across the accidental ground. Moreover, the danger of fire from arcing discharges through points of failure in the insulation of the low-voltage circuit due to the high voltage imposed upon it would be very great.

Now, as stated at the beginning of this part of the discussion, the life and property hazard arising from high potentials between low-voltage circuits and ground can be averted, or at least minimized, by permanently grounding some point of the low-voltage circuit through a low resistance. If this is done, and the resistance of the ground connection is low enough, no difference of potential can exist between circuit and ground which is great enough to be a serious menace to life or property. Protection is particularly easy to obtain in this manner if failure of insulation does not occur at more than one point, as set forth above. In this case—that is, with no accidental or permanent grounds on the high-voltage line—the current flow to earth is that due to the electrostatic capacity and leakage between line and ground, as represented in Fig. 2, and is relatively small.

If, however, the insulation fails at more than one point in the high-voltage circuit, or if the high-voltage circuit is intentionally grounded at another point, a condition may arise similar to that illustrated in Fig. 3, which renders protection somewhat more difficult. In this case 2200 volts are impressed upon two ground connections in series through the impedance of half of each of the low-voltage windings of the transformers. Since this impedance is small, it can be neglected for the moment, and it can be supposed

that the only check to current flow from A to B is that offered by the resistance of the ground connections. The potential difference between either low-voltage circuit and ground can, therefore, be expressed by $E=I\ R$, where I is the total current, R the resistance of either ground connection, and E the potential difference between the corresponding low-voltage circuit and ground, E being measured, of course, at some distance from the ground connection. If the resistance of the two ground connections under consideration are equal, and, as just stated, the voltage

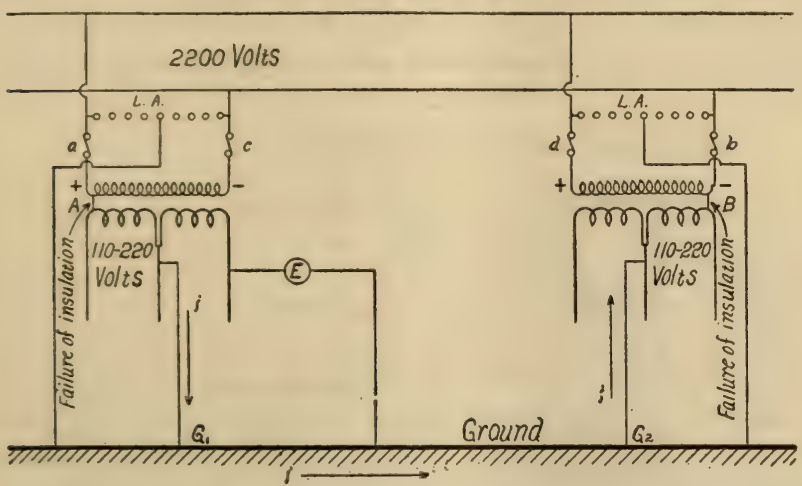


FIG. 3.—*Current from failure of insulation in two transformers flowing through ground connections G_1 and G_2 in series*

across the fault and half of the low-voltage winding is neglected, E will be 1100 volts.

As far as severity of current flow through the ground connection is concerned, Fig. 3 represents about the worst condition that could arise because of a failure of transformer insulation or a breakage of wires. But in this case—that is, where the failure is in the transformer—the current flow is limited by the transformer fuses. If the resistances of the ground connections are low enough fuses *a* and *b* will be blown when the failure occurs and break the circuit. This, of course, leaves fuses *c* and *d* intact, but the only current that can flow through the ground connections after fuses *a* and *b* are blown is that through the total impedance of both high-voltage windings in series, and this will be so small that there can be no serious rise of potential between the low-voltage circuit and ground. It should be added that the same result will be produced if one of the points of failure lies in a transformer and

the other at some point on the high-voltage line; that is, the fuses will blow and either isolate the transformer or reduce the current flow through the ground connection to a harmless amount, provided, as stated above, that the resistance of the ground connection is low enough.

With regard to accidental contacts between high-voltage and low-voltage wires, however, a condition may be presented which renders protection more difficult to obtain than either of those described above and which can be represented by connecting with a wire *A* of the same size as the line wire from the line side of the fuses in Fig. 4 to the low-voltage circuit. The flow of current through the ground connection is then definitely limited only by

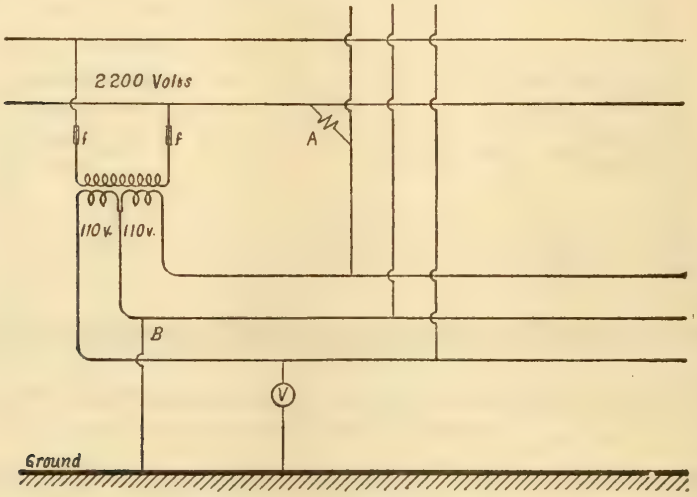


FIG. 4.—*Contact between wires*

such fuses or other circuit breakers as there are in the high-voltage line. Whether it reaches the limit set by the protective devices depends upon the current-carrying capacity of the wires, the resistance of the ground connection at *B* in series with whatever accidental grounds there are on the opposite wire of the line, and the impedance of as much of the transformer windings as happens to be in circuit. In extreme cases the current flow may easily reach hundreds of amperes.

From what has been said above, it is readily seen that, in order to avert danger from high potentials between low-voltage circuits and ground, considerable care is needed in making ground connections to secure low resistance and high-current carrying capacity. At the same time, however, it should be stated that

in all of the cases set forth above the conditions described represent the maximum degree of danger which may appear. It will sometimes occur that the points of failure in insulation will fall in such a relation to each other that the potential differences between low-voltage circuits and ground may be much lower than the full voltage of the supply system and the danger correspondingly less. But the chances that these points of failure will fall in such a relation to each other as to be harmless are negligible; and, moreover, in providing protective measures the full voltage must be taken account of because it will often be encountered. It should also be observed here that where low-voltage circuits are not protected against the development of high potentials against ground they must at all times be treated as dangerous. The frequency with which accidents occur from this cause is sufficient evidence of its seriousness.

The foregoing paragraphs apply to low-voltage circuits fed from 2200-volt single-phase supply systems with no ground connections on the high-voltage line mainly because this arrangement is simple and lends itself readily to illustrative purposes. It is a fact, of course, that a great many, perhaps a majority, of the distribution systems in use are 3 phase. These may be Y-connected 4-wire, with the neutral wire grounded either at the station, or at the station and also at intervals along the line. Or, the system may be Y-connected 3-wire with the neutral point either grounded or ungrounded. Some are delta-connected and ungrounded. But with any of these systems it is possible to have the full voltage of the primary winding of the transformer impressed upon the secondary circuit. Furthermore, if there is a permanent ground connection at the neutral point of the high-voltage circuit, there is needed but a single failure of insulation or contact between wires to produce practically full primary voltage between a low-voltage circuit and ground, and the current flow through any accidental ground or ground connection on the low-voltage circuit is limited only by the transformer fuses, or fuses in the lines, and the impedance in the circuit; that is, the condition is similar to that described above in the case of the single-phase ungrounded line where the capacity between line and ground is short-circuited by an accidental ground on one of the wires. On the other hand, with an ungrounded 3-phase system, the conditions with regard to flow of capacity current through the ground connection of a low-voltage circuit in the event of a

failure of insulation, or breakage of wires, at a single point on the line, are similar to those in the case of the single-phase circuit, only the capacity current per mile of line would be somewhat greater because of the fact that there are three wires instead of two. Moreover, with the ungrounded 3-phase system, to produce full-line voltage between a low-voltage circuit and ground requires that there be failures of insulation on more than a single wire of the circuit, the same as in the case of the single-phase system.

Before leaving this part of the discussion, it may be well to state that high voltages may appear in low-voltage circuits from causes other than faulty primary lines. The most fruitful sources of trouble of this sort are series arc circuits and street railway trolleys and feeders. Arc circuits are considered by some to be even more dangerous than primary lines, because in many cases lamps are hung from poles, necessitating bringing leads down past secondary circuits, and these lamps not infrequently fall from their brackets and bring not only the leads but sometimes a span of wire down with them. With an arc circuit in contact with an ungrounded low-voltage circuit, the difference of potential between low-voltage circuit and ground may be several thousand volts. In the case of railway trolleys and feeders, however, the greatest danger comes from the wires of low-voltage circuits breaking or sagging at crossings and resting on the railway conductors which are nearly always run underneath. Here, of course, the voltage hardly ever exceeds 550 to 700, but even voltages of this magnitude are very dangerous to life and property. Moreover, in arc circuits the current is limited to 6 or 7 amperes and hence may be taken care of by means of ground connections of only fair effectiveness without much trouble, but in railway circuits the only limits to the current are the generating capacity, the circuit breakers which are very large, and the resistance of the circuit, which makes protection more difficult. Nevertheless, by grounding those circuits with which the public comes in contact, it is possible at reasonable expense to provide a high degree of protection, not only from arc circuits but also from primary lines and railway circuits as well, and such grounding is a safety measure that should in no case be neglected.

(*d*) Point of Attachment of Ground Wires to Single-Phase Low-Voltage Circuits.—In connecting ground wires to single-phase low-voltage circuits, the usual practice is to connect to the middle wire of a 3-wire system as in Fig. 5, while with

a 2-wire system it is usually necessary to attach to one side of the circuit as in Fig. 6.[7] The chief advantage in connecting to the middle wire of the circuit lies in the fact that the voltage to earth under normal conditions of operation is then half of the total voltage. If it is found necessary to connect one side of the circuit to earth, the grounded side is at earth potential under normal conditions of operation, while the other side is at full voltage above ground. This is not a serious matter where circuits of 110 volts are concerned, but where the voltage is 220 or 440 it becomes important, and it is quite necessary for safety either that the middle point of the transformer winding be grounded, or that the circuit and apparatus and appliances connected to it be made accessible only from dry and well-insulated places, and have live parts specially guarded. (See National Electrical Safety Code, 92.)

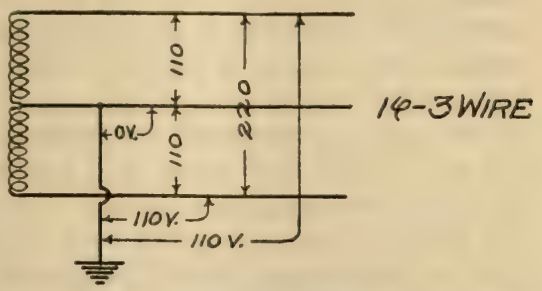


FIG. 5.—*Point of connection of ground wire to single-phase 3-wire circuits*

If a low-voltage circuit is fed by more than one transformer, a separate ground connection should be provided at each one, especially if there are junction fuses in the low-voltage circuit connecting the different transformers. Then, if the junction fuses are blown, there is no possibility of a single transformer and a part of a low-voltage circuit being isolated from the rest with no ground connection. Furthermore, ground connections may also be placed advantageously at the points where services enter buildings. These may be in addition to that at the transformer, or in lieu thereof, although the greater the number of ground connections the greater and more reliable the protection. The desirability of multiple ground connections on low-voltage

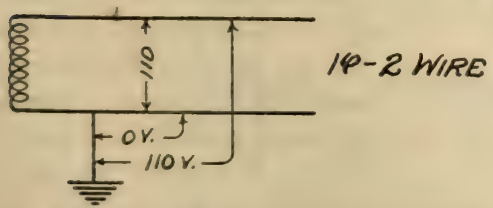


FIG. 6.—*Point of connection of ground wire to single-phase 2-wire circuits*

[7] See rule 92*b*, Appendix II.

alternating-current circuits is set forth in detail under Section IV, 5 (d).

As stated in the preceding paragraph, there should, in general, be a ground connection for each transformer. Moreover, this ground connection should be so attached that if the low-voltage circuit becomes disconnected in any way from the transformer, the low-voltage winding will still be grounded. This is particularly important if the high-voltage winding is still connected to the line, for if there is a difference of potential between high-voltage line and ground, an undue proportion of this voltage will be taken by the insulation between the low-voltage winding and case, which may result in a puncture. This is due to the fact that the electrostatic capacity between low-voltage winding and ground is small compared with that between windings—that is, if the low-voltage circuit is disconnected—and since any difference of potential between line and ground is shared in proportion to these capacities, a transient electrical disturbance on the line may puncture the insulation between low-voltage winding and case, this insulation not being designed to withstand high voltages.[8]

Mention should also be made here of the practice which is sometimes followed of using a common ground for a lightning arrester, a transformer core and case, and a low-voltage circuit. This is a good arrangement as far as the insulation of the transformer is concerned, but in the event of a discharge over the arrester, a high potential may be set up between low-voltage circuit and ground which may be a source of danger to a person touching fixtures at the time the discharge occurs. As shown more fully under Section III, 7, following, it is quite necessary to safety that a separate ground connection be provided for the lightning arrester.[9]

(*e*) Point of Attachment of Ground Wires to Polyphase Low-Voltage Circuits.—In general it may be stated that in grounding polyphase low-voltage secondary circuits, an effort should be made to attach the ground wire to the point in the circuit or to the circuit wire which will give the lowest voltages between wires and ground.[10] The reasons here are the same as for single-phase circuits, and where polyphase circuits are used for

[8] P. M. Lincoln, "Grounding of Low-Tension Circuits as a Protective Measure," convention report N. E. L. A., 2, p. 324, 1911.

[9] See rule 97*a*, Appendix II.

[10] See rule 92*b*, Appendix II.

lighting and power combined, apply with even more force because of the higher secondary voltage usually involved. Figs. 7 and 8 are diagrams of some of the polyphase transformer connections in common use. The voltage between phases in each case is

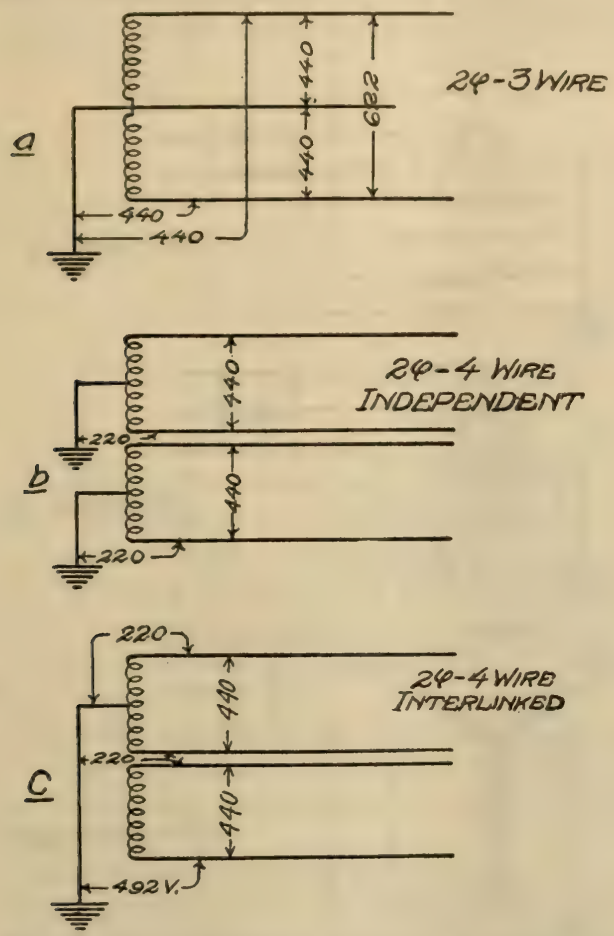


FIG. 7.—*Point of connection of ground wire to polyphase circuits*

supposed to be 440 and is chosen because it appears to be the one most commonly used in polyphase power circuits in practice, rather than because the intention is to recommend that circuits of this voltage be grounded. It may be well to mention that the National Electrical Safety Code requires that circuits in which the maximum voltage to ground does not exceed 150 be grounded, whereas grounding in the case of circuits of greater voltage to ground is left optional on the part of those responsible for them.[11]

[11] See rule 304, pt. 3, N. E. S. C.

Fig. 7, *a*, represents a 2-phase, 3-wire secondary circuit grounded at the middle wire. Here the voltage between either outside wire and ground is 440. To connect one of the outside wires to ground would put the other outside wire at 622 volts above ground, thus causing an increase in the life hazard over that obtained with a ground connection on the middle wire. Fig. 7, *b*, shows a 2-phase,

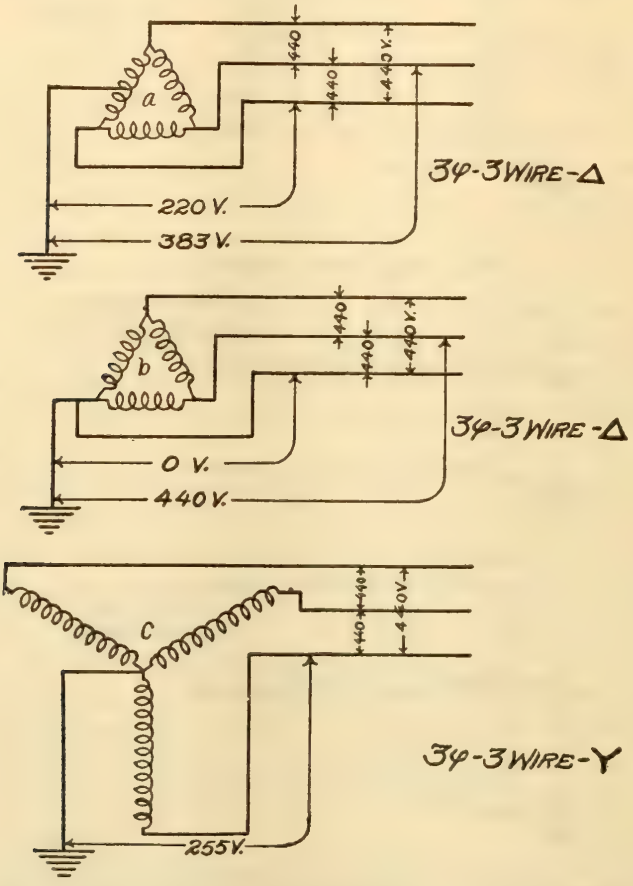


FIG. 8.—*Point of connection of ground wire to polyphase circuits*

4-wire circuit in which the phases are independent of each other. In this case the middle points of each winding can be grounded, if they are accessible, putting each of the four wires at 220 volts above ground. If the middle points are not accessible, one wire of each circuit can be grounded, which will give a voltage of 440 between each of the other outside wires and ground. In Fig. 7, *c*, the phases are interlinked within the machine taking energy from the circuit, so only one wire, or the middle point of one winding

can be connected to ground. The latter gives 492 volts between one outside wire and ground. The former gives 440 volts between two of the outside wires and ground.

In 2-phase circuits, therefore, the best points to ground are as follows: (*a*) Three-wire, at the middle wire; (*b*) 4-wire, independent, at the middle of each winding; (*c*) 4-wire, interlinked within the machine to which energy is being supplied, at the middle point of one of the windings.

In Fig. 8, *a*, is shown the secondary circuit of a 3-phase, 3-wire, delta-connected bank of transformers, such as is more or less generally used for power purposes, with the middle point of the winding of one of the transformers connected to ground. The maximum voltage to earth is 383, or 87 per cent of the line voltage. The minimum is 220 volts. In Fig. 8, *b*, is the same circuit with one corner of the delta grounded instead of the middle. Here, of course, one wire is at earth potential under normal conditions of operation, while the others are at full secondary voltage above ground. Fig. 8, *c*, represents a star-connected, 3-phase, 3-wire secondary circuit with the neutral point grounded, the voltage to ground of any wire being 58 per cent of the secondary voltage, in this case 255 volts. If the outer terminal of one of the transformers were grounded instead of the neutral point, one of the wires would be at ground potential under normal conditions of operation, while the others, as in 8, *b*, would be at full secondary voltage above ground.

In 3-phase circuits, therefore, the best points to ground are as follows: (*a*) Three-wire, delta-connected, at the middle point of the winding of one of the transformers; (*b*) 3-wire, star-connected, at the neutral point.

Fig. 9 gives some 3-phase secondary circuits not so commonly used as those mentioned above, but which are sometimes found very convenient in practice. In Fig. 9, *d*, a tap is brought out from one of the windings to give 115 volts for lighting. The most advantageous point to ground here is at the tap, because then one wire of the lighting circuit is at ground potential while the other is at 115 volts above ground. Any other point would give a greater voltage between points in the power circuit and ground, with no particular advantage in other ways. In 9, *e*, is shown a 3-phase, 6-wire, secondary circuit, sometimes installed for general utility purposes, in which the most advantageous point to ground is at the wire coming from the middle point of

one of the windings. This gives the lowest voltage to ground, amounting to practically the same thing as shown in Fig. 8, *a*. Wires 1, 2, and 3 can be used for lighting, with a maximum voltage to ground of 220, while 4, 5, and 6 may be used for power with a maximum voltage to ground of 383. Or, wires 1, 4, and 6 might

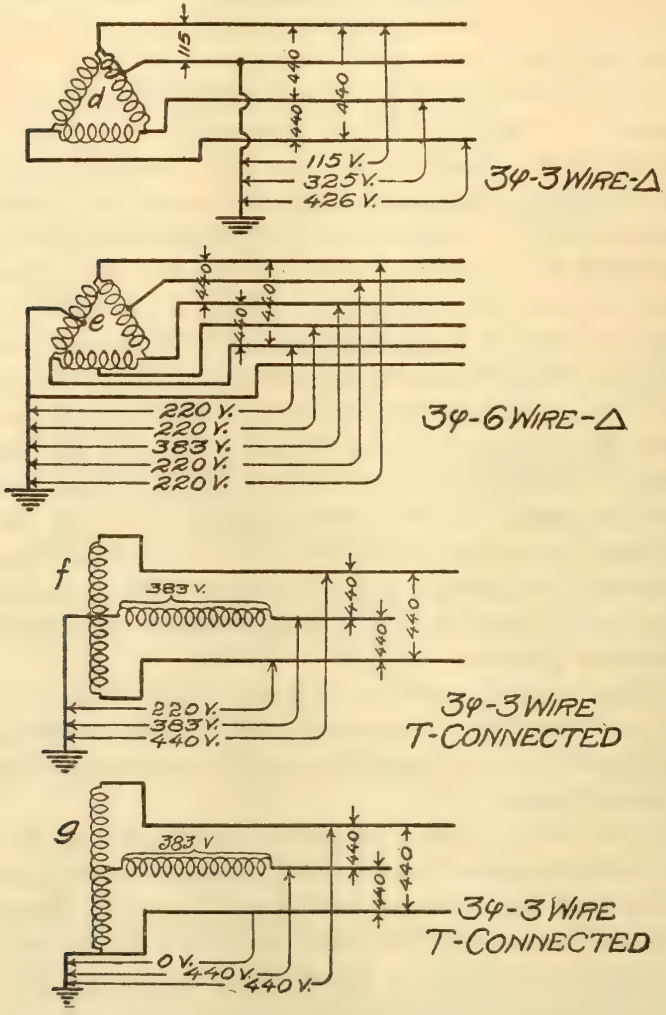


FIG. 9.—*Point of connection of ground wire to polyphase circuits*

be used for lighting with the same result. In Fig. 9, *f* and *g*, are represented the secondary windings of a set of T-connected transformers, in one case grounded at the middle point and in the other on an outside terminal. In the first, the maximum voltage to ground is 440, the minimum 383. In the second, one wire is at

ground potential, while the others are at full line voltage above ground.

To recapitulate, it appears that the most advantageous points to ground polyphase secondary circuits are as follows: (1) 2-phase, 3-wire, at the middle wire; (2) 2-phase, 4-wire, independent, at the middle point of each winding; (3) 2-phase, 4-wire, interlinked, at the middle point of one of the windings; (4) 3-phase, 3-wire, delta-connected, at the middle point of one of the windings; (5) 3-phase, star-connected, at the neutral point; (6) 3-phase, 6-wire, delta-connected, at the middle point of one of the windings; (7) where taps for lighting are taken from a delta-connected secondary, the best point is on the tap wire in such a way as to give the most favorable condition in regard to the lighting circuit; (8) in the case of the T-connected transformers, the best point is on one wire, because this wire is then placed at ground potential, whereas if connection is made to the middle point, all three wires present a high potential against ground.

It should be remembered, of course, that the real object in grounding polyphase as well as other circuits is to protect against high voltages from primary circuits and other sources, such as series arc circuits and railway conductors. There is, however, a life hazard from secondary voltages as well, and when grounding is done, this should, as indicated above, be taken into consideration and the ground connections be so disposed as to reduce it as much as practicable. It is not possible to state to what extent the life hazard from secondary voltages compares with that from high voltages but it is a fact that it gives some operating companies a great deal of concern, and they consider that much has been accomplished toward safety to consumers if in grounding to protect against high voltages the possible secondary voltage to ground due to faults in insulation is appreciably reduced at the same time. It is thought particularly important to give attention in this respect to lighting circuits taken from power-transformer installations, because here there is a possibility of dangerously high potentials appearing between the metallic parts of lighting fixtures and ground.

It may be added that there does not seem to be any possibility of an increase in the life hazard from secondary voltages in grounded secondary circuits as compared with those which are ungrounded, because, in order for an accident to occur with a grounded circuit, it is necessary for one accidental ground to appear, while with an

ungrounded circuit it is necessary for two to appear; but in the latter case, one may exist indefinitely without discovery, giving practically the same effect as a permanent ground connection, whereas in the first case an accidental ground will soon be discovered. Moreover, it is nearly always possible by grounding to reduce the potential to earth of the different wires of the circuit as compared with the potentials which might appear in the event of the formation of accidental grounds if the circuit were ungrounded.

(*f*) Effect of Resistance in Ground Connections for Low-Voltage Circuits.—From what has been said in the foregoing paragraphs it is evident that, in the event of a failure of insulation between windings in a transformer, or a contact between wires, the only definite limit to current flow to earth through the ground connection is that set by the nearest circuit breaker or fuse which will act to open the circuit. Moreover, the recognized safe maximum of potential difference between low-voltage circuits and ground, where the public as a matter of course comes in contact with apparatus and appliances connected to them, is about 150 volts. Hence, for a good degree of safety, the ground connection should be of such a character that it can carry currents ranging in value up to the limit set by the automatic circuit-opening devices just mentioned without the voltage between low-voltage circuit and ground rising to much more than 150.[12] In addition it must allow the passage of this current for a considerable period without an appreciable rise in its resistance, which would tend to increase the voltage between low-voltage circuit and ground. As shown below, the maximum resistance which will permit the fulfillment of these requirements can be readily ascertained.

In doing this, however, allowance should be made for the variation of resistance of ground connections with the temperature and moisture content of the earth The results of tests given hereafter will show that this variation from time to time may in some cases be as much as several hundred per cent, so when ground connections are installed it is advisable to allow a factor of safety to care for this contingency. The value of the factor to be used for any ground connection depends upon seasonal conditions; when made in very wet seasons a factor of safety of 3 may be used, whereas in very dry or very cold seasons 1 or even less may be acceptable. With a factor of safety of 1, the limit of voltage

[12] See rule 94*a*, Appendix II.

E in Fig. 3 at the time of installation would be 150. The maximum allowable resistance of the earth connection at the time of installation can, therefore, be expressed by $R = 150/Ia$, where Ia is the current rating of the nearest circuit breaker which will act to open the circuit in the event of an accident to insulation. If this current were 3 amperes R would be 150/3, or 50 ohms, 10 amperes 15 ohms, 100 amperes 1.5 ohms, and so on.

From these figures it may readily be inferred that little difficulty will be experienced in obtaining a good degree of protection by the use of ground connections where transformers and high-voltage lines of limited kilowatt capacity are concerned. But for high-voltage lines of large capacity, especially where contacts between wires are to be guarded against, it does not seem practicable to provide ground connections of such a character as entirely to avert danger under all conditions, unless connections to water pipes are used. In fact, to connect to water pipes is advantageous in any case and where there is opportunity for such connections their use is strongly to be recommended. The relative merits of water pipe ground connections and other forms are discussed in Section IV of this paper.

2. DIRECT-CURRENT DISTRIBUTION SYSTEMS

Direct-current distribution systems can be definitely divided into three classes so far as grounding is concerned, namely, trolley systems, 2-wire systems, and 3-wire systems. Trolley systems, of course, are not grounded, at least not in the sense implied by the term "protective grounds," so they do not need further discussion. In the other two, the purposes for which ground connections are used are, in the main, somewhat different and it is therefore desirable to consider them separately.

(*a*) Two-Wire Systems.—In 2-wire systems, the regular practice has developed of insulating the lines throughout and using ground connections only for the purpose of detecting accidental grounds. The reasons for this are as follows: If a 2-wire system is grounded it is generally necessary to attach the ground wire to one side of the circuit, and as pointed out above, this side is then at earth potential while the potential difference between the other wire and earth is equal to the full voltage of the line. A person touching this other wire would, therefore, receive the full line voltage of 110 or 220 volts as the case might be. This, however, is all that could occur under any condition of accidental

grounding on a circuit intentionally insulated, while during the time the insulation remained in good condition there would be no danger to life or property. As a consequence, unless the circuit is so situated that it may become crossed with high-voltage lines, there is no life hazard presented with it insulated that is not also presented with one wire connected to ground. Moreover, with one side grounded, only one accidental ground is necessary to bring about suitable conditions for starting a fire or producing electrolysis troubles, while with the circuit insulated an accidental ground on each wire is necessary to start a fire or give rise to danger of electrolysis. It may also be said that there is less danger of accidental grounds with the circuit insulated than with it grounded, for in the first case the stress on the insulation is shared by the two sides in series, while in the latter the full voltage of the line is taken by the insulation of one side, but the difference seems to be so small that it is of no practical consequence. Hence, since so little is to be gained by grounding 2-wire systems, they are in most cases insulated throughout and ground connections used only for the purpose of detecting accidental grounds.

The foregoing statement must be qualified, however, by adding that on a circuit which is completely insulated there is danger of an accumulation of static electricity of sufficient voltage to puncture insulation, and to remove this some form of ground connection is needed, but such ground connection may be of very high resistance. In fact, it will in most cases be found that the connection to earth formed by the ground detecting device will obviate all danger from static electricity. A further qualification is that if the circuit is exposed to contact with high-voltage lines it must be grounded as thoroughly as though it were an alternating-current secondary circuit fed from a high-voltage distribution system.

(*b*) THREE-WIRE SYSTEMS.—In the 3-wire system of direct-current distribution the extent of the lines is in most cases greater, and the total voltage higher than in 2-wire systems. The life and fire hazards presented by the usual 3-wire system are, therefore, appreciably greater than in the usual 2-wire system, and greater precautions are necessary to prevent accidents. On the other hand, the 3-wire system lends itself more readily to precautionary measures than the 2-wire system, in that the middle wire can be, and usually is, grounded, placing it at earth potential and making the potential difference between either outside wire and earth equal

to half of the total voltage. With the circuit insulated throughout, however, an accidental ground on one of the outside wires would put the other outside wire at full voltage above ground. If an insulated 3-wire circuit accidentally becomes grounded on one of the outside wires, there is, therefore, considerable danger to life as well as property, especially if the total voltage is 440, as it is in some instances. With the middle wire permanently grounded, there is, of course, still danger to property if an accidental ground forms on one of the outside wires, but if the resistance of the ground connection is low, an accidental ground does not appreciably increase the life hazard. Nevertheless, in the case of 440-volt circuits, the question of whether the life hazard presented by 220 volts continuously present between outside wires and ground is greater than that presented by the possibility of an accidental ground forming on an outside wire is at present unsettled. Hence, it has been deemed wise in preparing rules in regard to the grounding of circuits to require grounding only where the voltage to ground of any point of the grounded circuit does not exceed 150, and to leave cases where the voltage is greater to be grounded at the option of those responsible for them.[13]

The resistance of ground connections for 3-wire systems should be made as low as practicable. In fact, the lower this resistance is the better, and a perfect condition would be obtained only where the resistance to flow of current from the middle wire into the earth is zero. Zero resistance is, of course, not obtainable in practice, but by making use of water pipes or other available underground metallic structures a very low resistance (usually less than one ohm) can be realized. It should be stated here, however, as will be pointed out later, that it is advisable to ground the middle wire at but one point, and that at the station.[14]

The reasons for low resistance in ground connections for 3-wire systems are as follows: In the first place, 3-wire systems may in some cases become crossed with high-voltage lines, so a low resistance is desirable to prevent an undue rise of potential of the system against ground in the same manner as for low-voltage alternating-current circuits fed from high-voltage distribution networks; in the second place, one of the objects in grounding the middle wire of a 3-wire direct-current system is to keep the potential difference between either outside wire and ground as near half of the total voltage as possible. Now, if one of the outside

[13] See rule 304, pt. 3, N. E. S. C. [14] See rule 92*a*, Appendix H, N. E. S. C.

wires becomes accidentally grounded, current will flow through this accidental ground and the ground connection in series to the middle wire, as shown in Fig. 10, the normal potential difference between middle and outside wires being shared by the accidental ground and the ground connection in proportion to their respective resistances. The potential difference between the ungrounded outside wire and ground is evidently the sum of the potential differences between this wire and the middle wire and across the ground connection, this potential being measured at some distance from the ground connection as indicated at *E* in Fig. 10. Now, if the resistance of the ground connection is low, and that of the accidental ground high, there will be very little unbalancing of the potentials to ground of the two outside wires. These potentials will remain practically the same as under normal conditions

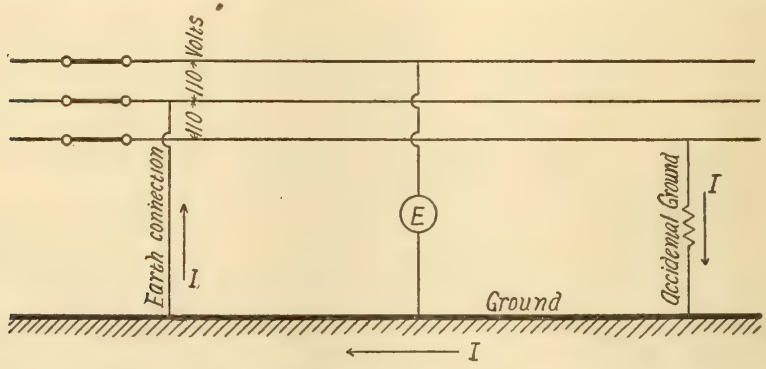


FIG. 10.—*Accidental ground on 3-wire direct-current system with middle wire earthed*

of operation. But if the resistance of the accidental ground is low, there may be considerable unbalancing of the voltages, not only between outside wires and ground, but also between wires if there is heavy current flow in them. Here service can be restored only by clearing the accidental ground, and in the meantime the line should be cut out manually if the automatic circuit-opening devices do not operate. On the other hand, if the resistance of the ground connection is high, there will be marked unbalancing of the voltage between outside wires and ground whether the resistance of the accidental ground is high or low. Hence, to minimize the bad effects of accidental grounds requires that the resistance of the ground connection be low. If it were of zero resistance, of course, there could be no unbalancing of voltages due to accidental grounds other than that attendant upon heavy current flow in the wires, and the nearer the resistance of the

ground connection approaches zero the more nearly the balance of the system will be maintained under all conditions of accidental grounding. The nearest approach possible to a ground connection of zero resistance is by connecting with a heavy cable to a large water main, which, in the case of most direct-current central stations, is not difficult of access.

3. DETECTORS OF ACCIDENTAL GROUNDS

The detection of accidental grounds is an important part of the operation of low-voltage distribution systems. Such grounds do not become apparent at once by affecting the operation of the system, and special means must, therefore, be resorted to in order to detect them. This is the case especially with direct-current distribution systems. The necessity for detecting these grounds arises from the life and fire hazards which they involve, and in direct-current circuits the possibility of electrolysis, but chiefly the fire hazard. The life hazard is not great because very special conditions are necessary to cause severe injury or death with 110 or 220 volts. Nevertheless, such accidents have occurred, mostly to persons who were at the time in damp locations, so the life hazard must be considered. In addition, if accidental grounds develop and remain undiscovered for a time, the resulting loss of energy, if the grounds are of low resistance, may become an important matter because the wasted energy must be paid for by either the consumer or the central station, depending upon the location of the points of failure of insulation with respect to the consumer's meter.

(*a*) Two-wire, Direct-Current Distribution Systems.—In the usual method of detecting accidental grounds on 2-wire direct-current systems a resistance sufficiently great to make the current flow through it small is connected across the line at the station and the middle point of this resistance connected to earth. Ordinarily there is no flow of current in the ground connection. If, however, an accidental ground develops on one side of the line, one-half of the resistance connected across the line is shunted by the ground connection in series with the accidental ground. Current then flows through the accidental ground and the ground connection to the opposite side of the line, causing the current flow in the two parts of the resistance just mentioned to become unequal; and by the use of suitable current measuring devices, not only can the presence of the accidental ground be

discovered, but also the side of the line on which it has occurred. The method would fail if accidental grounds of equal resistance should develop simultaneously on each wire, but the possibility that both grounds would be of the same resistance is exceedingly remote, and if there were a difference of resistance, the presence of grounds would be indicated. In any case the current flow carried by the ground connection of the detector is relatively small, being usually of the order of an ampere, and the resistance is, for that reason, not an important matter. The lower the resistance of the ground connection of the detectors, however, the better, because, with a low resistance, incipient grounds on the line can be more readily detected. The maximum allowable resistance would depend upon the character of the current measuring device used, and in every case where ground detectors are installed tests should be made to make certain that the resistance of the ground connection is of such a value as to make the device work properly.

The preceding paragraph applies to 2-wire, direct-current systems which are not grounded to protect against high voltages. Where such protective grounds are used, they will, as stated heretofore, generally be connected to one side of the line. Here one wire is at earth potential, so any accidental grounds that may form upon it are of no practical consequence. To detect accidental grounds on the other wire it is only necessary to ascertain when current is flowing in the ground wire, since when such grounds develop, current flow will take place through them and the ground connection in series to the opposite side of the line.

(*b*) THREE-WIRE, DIRECT-CURRENT SYSTEMS.—With the middle wire of a 3-wire, direct-current system grounded at a single point there is, ordinarily, no flow of current through the ground connection. If, however, an accidental ground should develop on an outer wire, current would flow through this accidental ground and the ground connection in series to the middle wire, the direction of flow depending upon whether the positive or negative side of the line had become grounded. In order to detect accidental grounds, therefore, it is only necessary to ascertain when current is flowing in the ground wire; its direction tells which side of the line the accidental ground is on. As in the 2-wire system without protective grounds, however, if accidental grounds of equal resistance should develop simultaneously on both sides of the circuit the method would fail, but the chances that this would occur are extremely small.

(*c*) Low-Voltage, Alternating-Current Systems.—In low-voltage alternating-current circuits which are permanently grounded at a single point, it is possible to detect accidental grounds in much the same way as in direct-current systems; that is, in 2-wire systems permanently grounded on one side, to detect accidental grounds on the opposite side, all that is necessary is to ascertain when current is flowing in the ground wire. If the middle point of the transformer winding is connected to ground, the same is true, but here the accidental ground may be on either wire and there is no way of telling which because there is no distinction as to direction of current flow. This also applies to a 3-wire system with a ground connection on the middle wire. In either case, however, if the current flow through the ground connection is heavy, it is possible to ascertain which wire the accidental ground is on by connecting a voltage-measuring device across each half of the transformer winding. The side on which the accidental ground has occurred will show a lower voltage than the other on account of the heavier current which it is carrying. In a 3-wire system there may be a difference of voltages due to an unbalanced load, but with current flow in the ground wire and a marked difference in voltage between the two sides of the line at the same time, it may safely be inferred that there is a serious accidental ground in existence on the side showing the lowest voltage.

With multiple grounds on the system the current flow due to accidental grounds is divided among the various ground connections in inverse proportion to their resistances. This makes detection of the accidental grounds rather difficult, especially on circuits having many points of connection to earth, because, even though an accidental ground of low resistance exists, if the current is divided among a hundred or more paths, it will not be easily distinguished from the small currents which always arise in ground wires from the fact that the permanently grounded conductor of the circuit operates in parallel with the ground connections; and when current flows in the grounded conductor, more or less current also flows through the ground.

Now, as pointed out later in a section devoted to multiple grounds, this current flow is of no importance save as it interferes with the detection of accidental grounds, but here its effects are of sufficient importance to prevent in a large measure the use of special ground-detecting devices in low-voltage alternating-current

circuits. In fact, in combination with other circumstances, it has made the use of these special ground detectors in practice the exception rather than the rule. For the most part, the development of accidental grounds is left to make itself apparent in meter readings, by blowing fuses, or by electric shocks to persons. In every case where it is practicable, however, such slipshod methods should be done away with and more suitable methods adopted instead.

When once an accidental ground has made itself apparent, it often turns out that it is in the customer's premises, where the electric utility has no power to remove it. The remedy lies with the consumer, and unless he sees that it is to his own advantage to apply it, the utility may have to choose between either discontinuing service until such time as the consumer becomes amenable to reason, or continuing it by cutting off all protective grounds and operating with the accidental ground still in existence. Since the utility usually does not wish to lose a customer or incur unfavorable public opinion by cutting off the service, the latter course is frequently followed. Temporarily this may be well enough, because it is not always possible for a consumer to clear accidental grounds immediately on discovering them, but in many cases, once the protective grounds are cut off, they are never reconnected. Such a condition should not be allowed to exist, for, in the first place, the consumer is in danger of fire in his premises and of electric shock to his family or employees. Moreover, although cutting off the ground wires may for the time being obviate the annoyance of running up large bills for wasted electrical energy, there is a possibility that an accidental ground may form on the other wire and run up a bill even while the consumer is dwelling in fancied security. In the second place, the use of protective grounds is a safety measure so well recognized in electrical practice that an accident in the consumer's premises while protective grounds are absent not only puts the electric utility in a bad light before the public, but puts it at a great disadvantage in the event of a damage suit ensuing. In view of these things, it is evidently to the great advantage of both consumer and utility that the accidental grounds be removed within a reasonable time.

It is, of course, out of the question to expect utilities to take drastic action in a case of this kind, and it is strongly to be urged that legislative bodies make rules requiring that service be cut

off unless circuits are put in operating condition within the time required to get the work done. The cost of finding and removing such accidental grounds may not be inconsiderable in some cases, but in the average case an electrician with a "megger," or other device for measuring the resistance of insulation, can search out and clear an accidental ground in a few hours at most. The cost is not to be compared with that which might result in a case of fire or personal injury.

4. MACHINE FRAMES

If the frame of a dynamo-electric machine is insulated from ground, and an accidental contact should occur between the frame or armature core and some part of the electric circuit, such as the armature winding, there would, in general, be a difference of potential between the frame and ground. The value of this difference of potential might be anything between zero and nearly full machine voltage, depending upon the location of the point of failure of insulation in the internal circuit and the condition of insulation of the external circuit. In the case of high-voltage machines with insulated frames, therefore, and also in the case of low-voltage machines which are connected through transformers to high-voltage circuits, a very serious risk to the lives of attendants is presented by the possibility of accidental grounds in the machines; and in order to avert, or at least greatly to reduce, this danger, the frames of such machines should be grounded. In fact, if the elimination of life hazard were the only factor to be considered, it would be best to ground the frames of machines of all kinds, mainly for the reason that there is great uncertainty as to the maximum voltage which is not dangerous to life. This, however, is not the general practice; and, moreover, it is a matter of common knowledge that in many cases even high-voltage machines are operated with insulated frames, except where rules are in force which require the grounding of the frames of all machines but those operating under special conditions. Such rules are in some cases included in city ordinances; in others fire insurance companies have certain rules, such, for instance, as the rule of the National Fire Protection Association which requires that the frames of machines operating at more than 550 volts be grounded, and that the frames of machines operating at 550 volts or less be grounded wherever feasible, or, if not feasible, that they be permanently and ef-

fectively insulated. Where companies operating machines assume the fire risk, and are not subject to regulations similar to those mentioned above, it not infrequently happens that machines of even very high voltage will be found with insulated frames. In view of the life hazard involved, this practice should be discontinued.

(*a*) INSULATED FRAMES.—The argument presented in favor of insulated frames is that such insulation safeguards machines and assists in maintaining continuity of service. Grounding frames is said to militate against safety of machines and continuity of service in the following ways: In the first place, it increases the stress on the insulation between electric circuit and frame, the voltage to ground with a grounded frame being taken entirely by the insulation of the electric circuit, whereas with the frame insulated the voltage to ground is shared by two layers of insulation in series, viz, the layer between circuit and frame, and the layer between frame and ground. The share of the total voltage taken by each layer is in direct proportion to its insulation resistance. Accidental grounds from failure of insulation, therefore, appear to be more likely to occur in machines with grounded frames than in machines with insulated frames. In the second place, with a grounded frame, an accidental ground in a machine may result in damage if there is an accidental ground or a ground connection in the external circuit, while on the contrary, if the frame of the machine were insulated, no damage would occur. This is said to be particularly the case with railway power-plant machinery feeding energy into a trolley system with ground return, and to a considerable degree, at least, with electrical machinery of all kinds.

It must be granted that the foregoing statements appear to be, in part at least, true; that is, in general, grounding frames increases the probability of damage by accidental grounds and this to the greatest extent in high-voltage machines. The principal reason for the latter is that in low-voltage machines and lines the factor of safety of insulation is relatively high—that is, as far as normal operating conditions are concerned—while on the other hand, in high-voltage machines and lines the factor of safety of insulation is much less, and in fact, may be said to decrease as the voltage increases. It is true, of course, that in low-voltage circuits the high factor of safety mentioned above is offset to a certain extent by ground connections in the external circuit, whereas in high-voltage circuits the total stress is in many instances shared

by the insulation of lines and machines in series. It is also true that the insulation of high-voltage circuits is less susceptible to damage by surges and high-frequency electrical disturbances than is the insulation of low-voltage circuits. However, because of the great disparity between high-voltage and low-voltage machines and lines as regards the factor of safety of insulation, and also because the insulation of high-voltage circuits is the most exposed to damage by electrical causes, there is no doubt that with grounded frames high-voltage machines are the most likely to be damaged, although it is not possible to say what the difference may be. Moreover, after an accidental ground has formed to a grounded frame, the resulting current flow to earth is the more destructive the higher the voltage of the machine, since it usually occurs that the higher the voltage the larger the kilowatt capacity and hence the greater the power for destruction. Insulating frames, therefore, appeals very strongly to many operating companies as a means of safeguarding their property and service, especially to railway companies, since, as just pointed out, railway power-plant machinery is by some considered to be more than ordinarily susceptible to the kind of damage described above.

With regard to life hazard, however, the opposite is the case; that is, with insulated frames the life hazard increases as the voltage increases. It is possible, of course, with insulating platforms and other devices to avert danger from this source, and the faithful observance of their use will result in a great degree of freedom from accidents. At the same time, safety here depends upon individual memory and carefulness, and in a case where the frame of a machine is in a safe condition for months or even years at a stretch, the observance of precautions in respect to it inevitably becomes lax. It is evident, therefore, that the best degree of safety lies in preventing a rise of potential between frame and ground by grounding the frame. Such grounding should be extended to machines of all voltages because, as previously stated, there is great uncertainty as to the maximum voltage which is not dangerous to life, although an exception may be made in the case of machines operating on lines supplying power at 150 volts or less which are not liable to contact with high-voltage lines. An exception may also be made in the case of machines where it is necessary to work on brushes when they are alive. But no exception can be made where machines of any kind operate in explosive gas or in very damp places; the frames here should in every case be grounded.

Now, in support of grounded frames there are several points which may be urged in addition to that of the safety secured to attendants. In the first place, whether in many cases insulating frames decreases the stress on the insulation of the circuit to an appreciable degree is open to question. For, in order that such insulation may reduce the stress on the insulation of the circuit, it is necessary that the insulation resistance between frame and ground be comparable in magnitude with that between circuit and frame, and unless it is, the benefits derived from insulating the frame are negligible as far as stress on insulation is concerned. In fact, if the resistance of the layer of insultation between frame and ground is low in comparison with that between electric circuit and frame, the frame might practically as well be grounded. There are, of course, certain types of machines, such as old type arc machines, in which the resistance of the insulation between electric circuit and frame is low, and here insulation between frame and ground would be of assistance, but such cases are exceptional. In the second place, insulating frames is conducive to carelessness in operation in that machines can be operated with an accidental ground to the frame or armature core, which is contrary to sound engineering practice. It enables the time of making repairs to be put off, and if the time of repairing can be put off at all, it will in many cases be postponed until something further happens, usually a second ground in the machine which may lead to damage of a more severe character than that produced by an accidental ground to a grounded frame. Furthermore, with insulated frames, accidental grounds are likely to develop without the knowledge of attendants, unless special means are taken to detect them. This is not often done, and incipient grounds may exist unsuspected until a burn out of the machine or a fatal, or at least serious, accident discloses the faulty condition.

On the other hand, without an appreciable increase of expense for operating purposes, machines with grounded frames can be safeguarded to an even greater extent than would ordinarily be the case with insulated frames, for with grounded frames devices continuously in operation for detecting incipient accidental grounds can be used, and in addition, tests can be made periodically which will show any progressive weakening of insulation. Incipient failures can thus be detected, searched out, and removed before anything serious happens, and in the meantime, the grounded frame guarantees safety to attendants from accidental

grounds which form without warning. In short, there is, in general, no advantage obtained in operating machines with insulated frames that can not also be had with grounded frames if a reasonable degree of care is used, and with grounded frames there is the additional great advantage of reduced life hazard.

To ground frames, however, may not in every case reduce the life hazard. Reference is had to one of the exceptions mentioned above, viz, where it is necessary to do work on the brushes of machines while they are alive. Here it is very easy for an attendant to come in contact with brushes and frame simultaneously with consequent danger to his life if the frame is grounded, but if the frame is insulated and an insulating platform built around it, the danger is reduced. With a grounded frame, even though an insulating platform is built around it, an attendant touching brushes and frame at the same time is liable to receive current not only from accidental grounds in the machine but also from accidental grounds on the external circuit, whereas if the frame is insulated, the danger arises only from accidental grounds in the machine. Hence, where it is necessary to work on the brushes of machines while alive, the best procedure seems to be to insulate the frame and build an insulating platform around it. On the other hand, where it is not necessary for attendants to come in contact with the electrical circuits of machines while they are alive, it seems better to ground the frames, mainly because there is then no possibility of an accident through carelessness.

(*b*) Ground Connections for Frames.—The resistance of earth connections for machine frames to give the best degree of safety can be determined in much the same way as for low-voltage alternating-current circuits; that is, it must be such that with a current flow to earth equal to the rating of the nearest circuit breaker which will operate to open the circuit to the machine in the event of an accident to insulation, the potential difference between frame and ground will not rise to a dangerous value. This rule can not be held to arbitrarily in all cases, however, because it may occur that soil and other conditions are such that a sufficiently low resistance to comply with the rule is impracticable of attainment, or it may be that an earth connection of very low resistance will result in unnecessary damage to a machine in the event of a failure of insulation. In such cases an approximately equivalent degree of protection to life can be obtained by making the resistance of the earth connection as low

as practicable and adjusting circuit breakers and other devices in such a way that, if current of a predetermined value flows to ground, the machine will either be cut out of circuit or insulated from ground by opening the earth wire. If the latter alternative is chosen warning can be given that the machine is in a dangerous condition, and it can be operated with due caution until it can be shut down for repairs. It should be emphasized here that under no consideration should a machine with an accidental ground to the frame be operated longer than is absolutely necessary.

5. CONDUCTING BODIES INCLOSING OR NEAR ELECTRICAL CIRCUITS

Coming under this head are those conducting bodies which, like machine frames but, in general, of less importance, are dangerous to life or property because of their proximity to electrical circuits. They may be enumerated in part as follows: Transformer cases, switch cases, cabinets, conduit, switchboard frames, cable armor, piping, in fact any metallic body inclosing or near an electrical circuit which is accessible to persons or is in a place where there are inflammable substances. On account of the great number of cases which would come under this head, they can not all be discussed in detail, but general principles can be pointed out and detailed discussion given to some of those which seem most important.

Danger from the conducting bodies under consideration may arise in two ways: In the first place, accidental contact may occur between the body and the electrical circuit, causing the body to become virtually a part of the electrical circuit unprotected by insulation. This is most likely to be the case with the conducting bodies which are in very close proximity to electrical circuits, particularly those which may, in strictness, be designated as metallic inclosures for electrical circuits, which include transformer cases, switch cases, cabinets, conduit, and cable armor. In the second place, persons may come in contact with electrical circuit and conducting body at the same time, or allow tools or other conducting objects to do so, which may, by arcing, cause shocks, burns, or fires. Accidents of this kind are most common with switchboard frames, piping, and structural metal. Of course, for such accidents to occur it is necessary for the electrical circuits to have bare, or at least unguarded parts.

(*a*) DANGER FROM ACCIDENTAL CONTACT BETWEEN METALLIC BODIES AND ELECTRICAL CIRCUITS.—In the case of accidental

contact between electrical circuit and conducting body the body takes the potential against ground of that part of the electrical circuit with which it is in contact. Moreover, unless the conducting body—that is, the transformer case, switch case, conduit, or whatever it may be—is intentionally grounded it is more than likely that it will simply be electrically isolated from ground. In other words, it will be connected to earth through a resistance of hundreds or perhaps thousands of ohms, instead of a few ohms, as it would be if it were grounded, or millions of ohms, as it would be if it were insulated from earth. Hence, if the condition of insulation of other parts of the circuit is such as to permit the flow of current, and the potential differences between electrical circuit and ground are such as are commonly found in practice, not only will the conducting body be at a potential against ground which may in many cases be dangerous to life, but there will be a flow of current to ground through the leakage path which may easily be the cause of fire through heating of inflammable substances if there are any present.

As an example may be taken a conduit through which passes a 440-volt, 3-wire, direct-current circuit with the middle wire grounded at the station, the conduit being isolated from earth by means of wooden or other inflammable supports as in a frame building or studded partition. In this case, if one of the outside wires should come in contact with the conduit through dampness or some other cause, the conduit would be at a potential of approximately 220 volts against ground. Current would then tend to flow through the accidental ground to the conduit and from there to earth through the leakage path and to the middle wire through the ground connection at the station, or to accidental grounds on the other outside wire of the line if there were any. If the resistance of the leakage path between conduit and ground were a few hundred ohms, heating might occur at points to a sufficient degree to cause fire, with a current of as little as an ampere or so. A current of this magnitude would easily escape notice even though ground detectors were used, and would be extremely likely to, if there were accidental grounds on the other outside wire, since grounds on both outside wires would tend to produce zero current in the ground connection. In the meantime a person touching the conduit would be likely to receive a severe shock if the locality were damp, or if for other reasons a good connection to earth were formed in some way through the body. Varying degrees of these dangers are presented by every ungrounded metallic inclosure

for electrical circuits and by all metallic objects near electrical circuits, being dependent upon the voltage of the circuit, its condition of insulation, and other factors. The frequency with which fires and electrical shocks due to this cause are reported is sufficient evidence of its seriousness.

The remedy for the condition described above as dangerous, is obvious; that is, to ground the conducting body. This rule is embodied in the rules of the National Electrical Safety Code, and also in those of the National Fire Protection Association. The latter rules are already enforced by underwriting inspection bureaus and municipal inspection bureaus wherever they have jurisdiction, but outside of these jurisdictions, unless regulations of similar character are enforced by other agencies, precautions against fire or accident are in many cases neglected.

Grounding the conducting body serves two purposes: In the first place, it allows sufficient current flow in the event of an accident to insulation to insure positive operation of ground detecting devices; in the second place, it tends to prevent the potential between conducting body and ground from rising to a dangerous value, and in addition, if the resistance of the ground connection is low enough, will serve to cut out a faulty circuit through the operation of fuses or circuit breakers. Thus, in a branch circuit fused for 6 amperes an accidental ground would result in a blown fuse if the voltage imposed were 150 and the resistance of the ground connection were as much as 20 ohms. With a branch circuit fused for 10 amperes, the resistance of the ground connection to produce a similar result would have to be 12 ohms, and so on.

It is readily seen that to produce results of this kind in circuits of large current-carrying capacity requires very low resistance in the ground connection, and here water pipes are of service. By their use a high degree of protection is obtainable. Where they are not available, however, other types of ground connections must be resorted to, but in nearly all cases a fair degree of protection can thus be obtained at reasonable cost.

(*b*) Danger from Contact with Electrical Circuit and Metallic Body at the Same Time.—With regard to conducting bodies near electrical circuits which are dangerous because persons may come in contact with conducting body and electrical circuit at the same time, or allow tools to do so, it may be said that such bodies should either be covered with a semi-insulating

material or isolated from earth, depending upon which is practicable; or both if necessary to obtain a minimum life and fire hazard. If, on the other hand, there is also danger that the conducting body may accidentally come in contact with the circuit at some point, it would probably be better to ground it, and, in addition, inclose those parts giving rise to the danger mentioned above with semi-insulating material or prevent contact in some other way. Where the sole danger, however, is from contact with persons or tools, isolation, where practicable, will undoubtedly be found to give the necessary degree of protection. This does not apply, of course, to metallic bodies which are of such construction that isolation is impossible, as it may be in the case of piping or structural metal. In such cases the desired protection can undoubtedly best be obtained by insulating or inclosing the metal with plaster or other fireproof material of considerable electrical resistivity.

The degree of protection obtainable where the circuit must be left exposed near the conducting body depends to a large extent upon the voltage of the circuit. In the case of low-voltage circuits where much work is done on lines and switchboards while circuits are alive, the greatest danger is from arcs formed by getting tools across the line or from line to a metallic body near by, more particularly the latter, because in respect to such conducting bodies there is naturally less care exercised than in the case of the line wires. If the metallic body is grounded, even through a considerable resistance, a severe burn may result; whereas, if the body is isolated—that is, separated from earth by a resistance of even a few hundred ohms—the flow of current would be insufficient to form an arc. Isolating, or covering with isolating material, therefore, gives a high degree of protection. In the case of high-voltage circuits, however, isolation can not always be depended upon for protection, but it is useful in many places. Moreover, the same necessity for the use of isolation does not appear for the reason that the circuits, in ordinary circumstances, should not be approached while they are alive. If work is to be done, they should be killed and securely grounded. Nevertheless, many times this precaution is frequently disregarded, or work is done on dead lines near lines that are alive, and under such circumstances the proximity of metallic bodies presents a certain degree of danger. There is also some danger, of course, even when working on lines supposedly killed and

grounded, because if a mistake is made and the line switched in, there may be a difference of potential against ground sufficient to be dangerous in spite of the ground connection. In any case, therefore, it is a wise precaution either to isolate such conducting bodies with the highest resistance practicable or secure them from contact with a covering of insulating or semi-insulating material, especially in places where work is often done.

(*c*) Railway Power-House Switchboard Frames.—One of the most important examples of a conducting body near an electrical circuit which may give rise to danger is that of the frames of certain types of railway power house or substation switchboards. At present it is a common practice among railway companies to ground these frames. This means, in the case of single trolley systems with ground return, virtually connecting the frame of the switchboard to the negative bus bar of the generating system. This by some is said to "fix" the potential of the frame. There is no doubt that the potential of the frame is "fixed" in this way, but a very undesirable thing is accomplished at the same time, namely, the positive bus bar and the frame are put in such relation to each other that in the event of a metallic connection being made between them the only limit to current flow is that placed by the generating capacity of the system and the current-carrying capacity of the circuit so formed. Now, in railway work it is sometimes very necessary to do repair work on switchboards while the conductors are alive, and in doing such work tools are likely to slip—in fact, sometimes do slip—and make contact with positive bus bar and frame. The heavy current flow which invariably follows causes an arc of tremendous size to form, and in many cases workmen have been either burned to death or maimed and disfigured for life. There is also a possibility of severe electrical shocks, although this is a minor matter compared with the effects of burns. Experience shows that the great majority of accidents on railway switchboards consist of burns received through short circuits between the positive bus bar and a grounded switchboard frame. In view of the consequences of such accidents, the grounding of the frames of those types of railway power-house switchboards in which the bus bars are exposed and sufficiently close to each other, or to the frame, to permit short-circuiting by tools of ordinary length must be regarded as increasing the hazard and should be discontinued. The potential of the frame can be just as definitely

"fixed" by mounting the frame on a concrete base as by grounding, concrete being a semi-insulator when air-dried. There is, then, a high resistance interposed between frame and ground which eliminates any danger of arcs being formed between frame and positive bus bar by accident. A very serious menace to the lives of workmen is thus removed, and although there still is the possibility of electric shock, severe injury in this way is not likely to occur if reasonable care is used. To prevent shocks an insulating platform may be built around the board and near-by metallic bodies insulated or inclosed by insulating material.

It may be added that in those types of switchboards where bus bars are out of reach of persons and too far apart, and too far from the frame to allow short-circuiting by tools there is no objection to grounding.

(*d*) INTERIOR FIXTURES.—An important class of metallic bodies inclosing electrical circuits is that which includes the metallic inclosing shells of interior electric fixtures, such as the shells of lamp sockets and chandeliers. More persons come in contact with these than with any other form of electrical equipment, and it is, therefore, exceedingly necessary that they be made safe by grounding through as low a resistance as it is practicable to obtain. Otherwise they may become dangerous on account of accidental grounds forming within them which puts them at the potential above ground of the circuit which they inclose. Or, if accidental contact occurs between the low-voltage circuit and a high-voltage circuit, arcing discharges to the shell may occur, making it very dangerous to approach, especially in damp places.

In grounding these shells it is well to observe certain precautions: First, in every case separate ground wires should be provided—that is, fixtures should not be connected to the ground wire of a circuit or a lightning arrester, for, if they are, in the case of a current or lightning discharge passing over the ground wire, a high potential may be impressed upon the fixture due to the impedance of the ground wire and the resistance of the ground connection. Second, in no case should a fixture be connected to a grounded wire of a circuit, because in the event of an accidental contact between the low-voltage circuit and a high-voltage line, the grounded conductor of the circuit is liable to a potential rise above ground, due to the resistance of the ground connection, which may not be dangerous when impressed only upon the circuit itself, but which, when impressed upon the fixture, may be

a menace to life. Finally, grounding of fixtures is important everywhere, but is especially so in damp places and in places within reach either by hand or foot of grounded metal, such as water and gas pipes and steel building frames.

As a special precaution in basements, bathrooms, refrigerating rooms, or places of any kind where damp processes are carried on, porcelain or weatherproof sockets may be installed. In so far as these can be made use of, they obviate the necessity for grounding, but it is not practicable to do away with metal entirely, so a certain amount of grounding is usually necessary. In some places, as set forth below, grounding is relatively a simple matter because near-by metal can be used, but in others a long separate ground wire may be required. To this, however, any number of fixtures may be attached if it is desirable to do so.

(*e*) Grounding in Large Buildings.—A matter which should be mentioned is that to obtain the effect of grounding does not in every case require connection to the earth itself. In a large building, for instance, which contains electric circuits in conduit, water and gas piping, structural metal, and other metallic bodies, it is in some cases desirable to isolate from earth all of the metal within the buildings to prevent electrolysis by stray currents from outside. To this end, it may be advisable to put insulating joints in water and gas pipes were they enter the building. As a rule, the metal work is then interconnected electrically and allowed to remain isolated from earth. Conduit, transformer cases, fixtures, or other conducting bodies may be considered as made sufficiently safe if they are connected to such an interconnected mass of metal. No difference of potential can then exist between them and surrounding conducting objects which will be dangerous to life. It is as necessary as before, however, that devices for detecting accidental grounds be installed in the building, using the interconnected metal as earth. It should also be emphasized that under no conditions should an accidental ground be allowed long to exist, because of the dangers already discussed and the further danger in some cases of electrolysis. As before stated, if an accidental ground is allowed long to exist, there is, in addition to danger from electrolysis, a certain degree of danger to life and also of fire, even though the most elaborate precautions as regards grounding are taken.

In conclusion it may be stated that to ground electrical circuits to the electrically isolated metal work of buildings is objectionable

in that there is a possibility, in some cases, of damage by electrolysis, and in others, that the metal work may attain a high potential against ground due to the entrance of high voltage from primary distribution lines or arc circuits with a consequent danger to life and property. In grounding electrical circuits connections, therefore, should be made either outside of buildings, or if within buildings, to metallically continuous structures extending into the earth at or near the point where the electrical circuit enters.[15]

6. HIGH-VOLTAGE TRANSMISSION AND DISTRIBUTION SYSTEMS

The use of permanent ground connections in high-voltage transmission and distribution systems is limited largely to grounding the neutrals of 3-phase, 3-wire, and 3-phase, 4-wire circuits for the purpose of averting electrical dangers to lines and plant equipment and in that way improving operating conditions. Grounding for this purpose is by no means general, however, and there are many adverse opinions as to its use in any case. The chief danger averted in this way is that due to accidental grounds which may lead to destructive oscillations or short circuits, underground cables being more susceptible to damage from these causes than aerial lines. By grounding the neutral, such accidental grounds can be turned into short circuits on one phase as soon as they are formed, and through the operation of circuit breakers, automatically cut out the faulty cables before the grounds develop into short circuits between phases. In general, the cable will then be left in such a condition that by means of well-known methods for locating accidental grounds, the approximate location of the fault is possible; whereas, if the accidental ground is allowed to develop into a short circuit between phases, such location is practically impossible, except by sectionalizing the cable at manholes and testing each section by itself. This method of protection is used in many underground systems, although it has certain disadvantages, and is used to a less extent in aerial lines. The chief disadvantage is that an accidental ground on one phase of a line immediately cuts that line out of circuit; whereas, in the interest of continuous service, it is in many instances desirable to operate a line temporarily, even though one phase is accidentally grounded.

In that case the resistance of the ground connection must be such as to allow a sufficient flow of current to trip the circuit

[15] See rules 95 *a* and *b*, Appendix II, N. E. S. C.

breaker having the highest current setting of any in the system, and still not put a heavier strain on the generating equipment than is absolutely necessary. The total resistance required will, therefore, depend upon the current-carrying capacity of the largest feeder and the voltage at which the system is operated. Furthermore, this resistance must not be fluctuating to any great degree. In the past, the desirability of limiting the current flow has been recognized, but in many instances the ground connection has been assumed to be of zero resistance, and in order to limit the current flow, rheostats have been placed between the neutral point and earth, the impedance of the rheostats being calculated without regard to the resistance of the ground connection. In the event of an accidental ground, it was found, of course, that the current flow was less than was expected.

In nearly all modern systems, the resistance required between neutral and earth is such that the resistance of the ground connection need be but a small part of the total, but it must always be taken into account. Rheostats may, therefore, be placed in the neutral connection, and in that way not only can the current be limited to the proper value, but fluctuations of the total resistance minimized; that is, in comparison with what they would be if the ground connection itself were depended upon to furnish all of the current-limiting resistance. Heretofore, the rheostats used in some large 13 000 to 20 000-volt systems ranged from 6 to 20 ohms, so a ground connection of 1-ohm resistance or less should give satisfactory results in such cases. The energy absorbing capacity of the ground connection need not be great unless it is planned to use the earth as a conductor if one phase is disabled. In that event the ground connection must be able to carry the full load current of one phase continuously without an appreciable change in resistance. Ordinarily, however, where the ground connection is supposed to carry current only for a sufficient length of time to trip a circuit breaker, the energy absorbing capacity is of little importance, since, though the currents carried are large, they flow for only a short time.

Grounding the neutral is also used in connection with 3-phase, 4-wire distribution systems for the purpose of preventing undesirable fluctuations of voltage in low-voltage circuits and differences of potential between the neutral wire and ground. As long as the insulation resistance of each wire to ground is the same, there is, of course, no necessity for grounding; but this is rarely

the case, at least for any length of time, and to guard against the unbalancing effects of accidental grounds of high resistance it is necessary to ground the neutral wire. The resistance required of the ground connection in this case depends upon the extent of the system, the voltage, and other factors. In general, it may be said that the current carried by such a ground connection will be of but a few amperes in strength; that is, of the same order of magnitude at the charging current of the line. The ground connection should be such as to carry this current for considerable lengths of time without change of resistance or a voltage drop appreciable in comparison with the voltage of the system. If the ground connection is expected to serve two purposes, namely, that of eliminating the unbalancing effects due to leaks, and also of cutting out faulty lines when accidental grounds of low resistance develop, it will almost always be found that if the resistance of the ground connection is suited to the latter purpose, the first will be more than amply served.

7. ELECTRICAL SYSTEMS UNDER CONSTRUCTION OR REPAIR

Electrical systems under construction or repair should, when possible, be disconnected from the source of energy and grounded temporarily for the protection of workmen employed upon them. In general, workmen are liable to electrical dangers from three sources when so engaged: First, the line on which they are working may be switched in by mistake; second, danger may arise from atmospheric electrical disturbances; third, there may be danger through leakage or induction from other lines. With regard to the first, it is best guarded against by suitable operating precautions such as locking and labeling switches; and further, by short-circuiting the line at the point where the work is being done. In addition to these precautions most companies require that the line be grounded, if there is even a slight possibility that danger is likely to proceed from the second and third sources named above.

(*a*) Danger to Workmen from Atmospheric Electricity.—There is a very real danger from atmospheric electric disturbances which may set up large differences of potential between line and ground, especially in long aerial lines. In underground lines such disturbances are in most cases of little moment unless part of the line is overhead and the rest underground, in which case atmospheric electric disturbances originating in the aerial portion of the

line may, in a measure, affect the underground portion. In aerial lines the greatest danger comes from lightning striking the lines directly, the effects of which may be carried many miles with sufficient force to kill a person. This extreme danger is likely to arise, of course, only during the lightning season; but aside from this, it is necessary at all times of the year to guard against the effects of accumulated or induced charges. Grounding the line is the most effective remedy and is to be regarded as important in any case, and especially so during the lightning season. Complete protection, of course, is not obtainable, for, even though the line is grounded at short intervals, through a low resistance, a near-by lightning stroke is extremely dangerous. Therefore, when thunderstorms are in the immediate vicinity of the line it is desirable to suspend work until the danger is past, or at least until greatly lessened. This is especially the case with workmen on the ground handling wires which are connected to the line. Workmen on poles, on the other hand, are not in as great danger as those on the ground, and the same may be said of workmen on steel towers, if the line wires are electrically connected to the towers.

In grounding lines to avert danger from atmospheric electric disturbances, the inability to provide complete protection mentioned in the preceding paragraph is due to the fact that a large part of such disturbances either originate or end in high-frequency effects. With such high-frequency effects large differences of potential may exist between parts of the line and ground in spite of all the grounding that is practicable. On the other hand, grounding to relieve steady electrostatic stress between line and ground in a successful manner is readily done, and moreover the resistance of ground connections for this purpose is not an important matter. Ground connections at intervals of a few thousand feet, the resistance of such connections being 20 ohms or so each, will be found sufficient protection against accumulated charges. Such ground connections may in a measure also protect against high-frequency effects set up by direct strokes of lightning. In fact, as stated above, it is doubtful if any practicable amount of grounding would be sufficient to give complete protection against direct strokes of lightning, even though the strokes be several miles away from the place where work is being done. The best procedure, therefore, seems to be that of grounding the line to protect against accumulated charges, and in the event of severe

lightning disturbances in the immediate vicinity, to keep away from the line until the disturbance ceases.

(*b*) DANGER THROUGH LEAKAGE FROM NEIGHBORING LINES.—Danger from leakage and induction from other lines is present, of course, only where lines of sufficient voltage to be dangerous to human life are near the line under construction or repair. If there is such proximity between lines, it must, in all cases, be considered as a source of danger and the maximum degree of danger provided against. The maximum degree of danger arises when a direct contact occurs between the lines in a manner similar to that illustrated in Fig. 4 for the case of low-voltage transformer windings. In the event of such a contact between the lines, the only definite limit to current flow is that set by the protective devices in the live line with which contact is made. The resistance of the ground connection must, therefore, be such as to allow a sufficient current to flow to operate these protective devices without a rise of potential between the protected line and ground that would be great enough to be dangerous to human life. As mentioned heretofore, 150 volts is considered as the maximum voltage to which persons can be subjected with safety. The maximum allowable resistance of the ground connection can, therefore, be expressed by $R = \frac{150}{\text{Current}}$, where the current is that required to operate the fuses or circuit breakers which protect the live wire from overload. This appears to give a very low resistance for such ground connections, especially where circuits of large current capacity are to be guarded against, but nothing greater than the result given by this formula can be considered as giving a "sufficient ground connection" as defined by most safety rules. To provide such ground connections will, however, rarely work a hardship. The need for them appears principally in urban districts where underground metal structures of great extent are plentiful and easy of access. Moreover, in plants and substations permanent connections can be made with terminals provided for convenient attachment, while in other places connections can be made to water pipes as occasion requires. On isolated rural lines the grounding required will rarely exceed that described in the preceding paragraph.

When lines are grounded temporarily, it is very desirable that the electrical characteristics of the ground connections used be known; in fact, it is almost as desirable as where permanent grounds

are made. This is always possible in the case of grounds made at stations, for here the safety arrangements are more or less constantly in use and can be made permanent, the resistance being checked periodically. In the field, however, it is not always practicable to make measurements, and it may be necessary to rely upon inspection only. To one familiar with soil conditions in a particular locality this may be sufficient, but in general, reliance should be placed on unmeasured ground connections only in emergencies, or in cases where it is very evident that severe conditions will not be met by the safety arrangements. In every case measurements with ammeter and voltmeter or Kohlrausch bridge should be made if practicable.

In making ground connections such as those just described, there is an incentive to use hasty methods, but for the sake of safety it is wise to make such connections secure. Clamps may be considered sufficiently secure if they are of sturdy construction. The ground wire should be of the same size as the line wire to which it is attached, and bolted or soldered to the clamps, one of which should be a spring clamp for attaching to the line. In grounding the line the ground wire should first be clamped to the water pipe or other conductor which serves as the ground connection. Then with a switch hook the spring clamp may be sprung over the line wire, which obviates the necessity for touching the line in any way while there is a possibility that it may be dangerous.

8. LIGHTNING ARRESTERS AND OVERHEAD GROUND WIRES

Since lightning arresters and overhead ground wires protect life only indirectly and are designed almost solely for the purpose of protecting plant equipment and lines from lightning and overvoltages, the discussion herein given to ground connections for them will be brief and devoted largely to pointing out the dangers that may arise from the improper use of such ground connections.

(*a*) Danger from Improper Use of a Ground Connection for a Lightning Arrester.—The chief danger which may arise is brought about by connecting to the ground wire of the lightning arrester those metallic bodies which it is desirable to ground to promote personal safety. These bodies include transformer cases, machine frames, low-voltage circuits, and others. Regarded only from the standpoint of strain on insulation between electrical circuits and ground or between high-voltage and low-voltage circuits, due to lightning or other disturbances, there is a distinct

advantage in thus connecting to the ground wire of the lightning arrester, because in that case the strain on the insulation is limited to that accompanying the drop in voltage across the arrester while it is discharging; and by proper design of the arrester, this strain can be made comparable with the strain on insulation under normal conditions of operation, excepting, of course, those cases in which there is a marked effect from the time lag in the discharge of the arrester. As a consequence, the use of the lightning arrester ground connection for the purpose of grounding transformer cases, low-voltage circuits, and the like, has been many times recommended and is now practiced by many companies.

The greatest objection to it, however, is this: In many cases the resistance of the ground connection is high, and in fact, in all cases there is some resistance in the ground connection. Moreover, it may take a long wire to reach from the ground end of the arrester to the point where actual contact with the earth occurs, especially if the soil near the arrester is not suitable for making ground connections, so the high-frequence impedance in the ground wire may be considerable. Now, the rate of discharge over an arrester may be very great. In fact, some of the recent designs of lightning arresters for distribution circuits place the maximum discharge rate of the arrester at 650 amperes,[16] experience having shown that it is unsafe to assume a lower maximum discharge rate than this. Hence, in the event of a severe lightning stroke passing over the arrester, the potential between the ground end of the arrester and earth may be hundreds, or even thousands, of volts, this voltage to ground being imparted to whatever metallic bodies are connected to the ground wire at that point. Obviously, a person in contact with one of the metallic bodies at the time of the stroke would be likely to receive a severe shock, and there would also be a likelihood of sparks from them to ground which might be dangerous in some cases.

It is desirable, therefore, to give the lightning arrester a separate ground connection [17] in every case if it is possible and connect transformer cases and other metallic bodies to the arrester ground wire only when they are inaccessible to persons. This will be found to be the case in some instances, but where persons can come in contact with the grounded metal, such interconnection should be avoided carefully. The same is true of earth connections for overhead ground wires.

[16] Creighton and Shavor, Trans. A. I. E. E., **31**, p. 811; 1912. [17] See rule 97*a*, Appendix II, N. E. S. C.

A word may be said here with regard to low-voltage alternating-current circuits. It has been recommended by some that the cores and cases of the transformers feeding such circuits be connected to the earth wire of the lightning arrester and a short spark gap placed between the earth wire and the middle wire of the low-voltage circuit. This spark gap is supposed to break down and relieve any high potential difference between low-voltage circuit and ground. A gap of this kind may be efficacious under certain conditions, but in the event of a lightning discharge across the arrester, it would offer no protection to persons who at the time were in contact with the low-voltage circuit. As a matter of fact, the spark gap would break down and a part of the lightning discharge tend to go to ground through the person's body. Such spark gaps should, therefore, be excluded unless there is no danger to persons, or probability of fire, if a high-potential should exist between the low-voltage circuit and ground. To gain the maximum degree of protection, the middle wire must be solidly grounded, as pointed out in this paper, and that separately from the ground connection for the lightning arrester. It may appear that to be obliged to install two ground connections at a single installation would work a hardship, yet in many cases personal safety demands it. It should be mentioned, however, that there is no objection to grounding a lightning arrester and a low-voltage circuit or a metallic body to a water system at points near each other, unless the resistance of the water-pipe ground connection is extraordinarily high, or the main is reached only through a long service pipe. In the latter case a separate ground connection for the arresters would be advisable.[18]

(*b*) Effect of Resistance in the Ground Connection.—The actual resistance allowable in a ground connection for a lightning arrester depends to some extent upon the character of the equipment it is intended to protect. Moreover, this resistance is important only in so far as it is a factor in increasing the impedance in the path of the lightning discharge through the arrester to ground. In general, it should be made as low as practicable for the following reason: When a discharge takes place over an arrester, the impedance offered to the discharge to ground should be as small as it can be made in order to relieve the line of strain as quickly as possible. It is only after the initial discharge has occurred that a high resistance in the arrester circuit is desirable

[18] See Rule 97*b*, Appendix II.

for the purpose of preventing an arc being formed by the line current. Various devices are used to produce a sudden increase of resistance of the arrester circuit, most of which make use of the line current following the initial discharge to produce the desired result. Among these may be named the electrolytic lightning arrester. The multigap arrester makes use of the cooling properties of the arc vapors of certain metals. Both of these are quite efficacious in increasing the resistance of the arrester circuit enormously during the passage of the line current after the lightning discharge for the time of a half cycle, or two or three cycles at most. In this case, therefore, resistance in the ground connection only works to interfere with the effective operation of the arrester and should be reduced to the lowest practicable limit.

On the other hand, arresters protecting circuits which carry currents at low voltage, such as telephone and telegraph lines, seem in practice to operate more or less satisfactorily with considerable resistance in the ground connection. Ground connections in these circuits of 40 or 50 or even several hundred ohms resistance are not uncommon. Their effectiveness, however, is probably due to the prevalence of mild lightning discharges on such lines. Moreover, as a rule, there are a large number of such circuits on each pole line and many arresters on each circuit, so that a lightning stroke may often be divided and carried off through a number of arresters in parallel. Nevertheless, heavy discharges are likely to cause severe damage. The only advantage of resistance in the ground connection in any case is that it tends to damp out oscillations in the arrester circuit. The lowest resistance readily obtainable in practice may be considered sufficient for this, however, and the greater the resistance the greater the disadvantages in other directions.

9. LIGHTNING RODS

The ground connection is the most vital part of a lightning rod system. If it is poor, the effectiveness of the system is greatly diminished. Moreover, the conditions under which a ground connection for a lightning rod must operate are severe. In the first place, inspection is usually lax, there being no responsible utility concerned, and the average owner seems to think that a lightning rod should remain operative without attention as long as the average building lasts. The cause of this inattention is probably to be found in the fact that a lightning rod is

called upon to operate only infrequently. As a consequence, unless specific arrangements are made for periodical inspection, it is likely that inspection will be omitted entirely, or at most be made very irregularly and inadequately. Therefore, in order that assurance may be had that rods will be in good condition when their services are required, it is necessary for persons installing them to provide ground connections that will successfully withstand corrosion and which are well protected from mechanical injury. In the second place, the currents and potential differences involved in lightning strokes are enormous. The maximum current may, in some cases, be as much as 25 000 amperes,[19] and furthermore, the steepness of the wave front of the flash may be the equivalent of hundreds of thousands of cycles per second. Consequently, in the event of a stroke, high potials may be set up between the lightning rod and ground, sufficient in many cases to break down large air gaps. The magnitude of these potentials may be estimated by simply multiplying the assumed maximum current of a lightning stroke by the resistance of the ground connection. Ordinarily, ground connections for lightning rods, as now installed, have a resistance of many ohms, 10 ohms being a rather low value which may be assumed for calculation. Since, as pointed out above, the maximum current of a lightning flash may be as much as 25 000 amperes, it is readily seen that the potential between rod and ground when a stroke is passing may reach a value of 250 000 volts. This does not include, of course, the component of the voltage taken up by the inductance of the rod, which may be greater or less than that taken up by the resistance of the ground connection. Hence, it is obvious that extremely dangerous potential differences may exist instantaneously between rod and ground.

In the installation of lightning rods, therefore, great care has to be exercised to obtain maximum practicable effectiveness. Long life of all parts of the system must be assured, and the rods and ground connections must be disposed to the best advantage. Since the inductance of a divided circuit is less than that of a single circuit, it is desirable to have the system come to earth at a number of places as far removed from each other as the contour of the object to be protected will readily allow. Moreover,

[19] Pockels, Annalen Phys. Chem., **63**, p. 195; Annalen Phys. Chem., **65**, pt. 2, p. 458; Phys. Zeit., **2**, p. 306.

the greater the number of such grounds, the better, having regard, of course, to the economical use of material. In no case should there be less than two points of connection with the earth, unless the object to be protected is a tree or a flagpole; in these cases a single ground connection is all that is practicable. The multiplicity of down conductors minimizes the inductance of the system, while that of the ground connections minimizes the resistance. It may also be stated that a number of ground connections in parallel at a distance from each other, even though each is of high resistance, is better than a single ground connection of low resistance. The total resistance to earth should in any case be made as low as practicable.

In making a ground connection for a lightning rod, it is necessary to make contact with the stratum of permanently moist earth nearest the surface of the ground. Ground connections in wells or other places where the actual contact with the earth occurs only at considerable distances below this stratum are not to be relied upon for protection for the following reason: If conditions exist for a lightning discharge between cloud and earth, the charge on the earth induced by the cloud charge resides at the surface of the ground if it is moist, or if it is not, then at the surface of the uppermost stratum of moist earth. This is in accordance with experimental knowledge of electricity; that is, the effects of an electric charge are not manifested beneath the surface of a conductor. Moreover, that this is the case with lightning charges is indicated by the fact that a lightning discharge to earth where the surface is damp leaves scarcely any marks; whereas in desert regions, or very dry places, fulgurites are formed or the ground is torn up, showing that the lightning stroke has penetrated the ground. In making ground connections for lightning rods, therefore, contact with the uppermost stratum of moist earth is absolutely essential to the safe operation of the system, for when the discharge occurs, the charge on the surface of the ground will tend to rush into the rod, and this will occur by the most direct path. If the ground connection makes contact much below the uppermost stratum of moist earth, the discharge will leap to the rod at the surface of the ground instead of traveling downward to where contact is made with the earth and then back again.

As an example, the Washington Monument in the District of Columbia may be cited. When the first lightning rod equipment was put on the Monument, a ground connection was made by dig-

ging a well 33 feet in depth below the bottom of the drum pit, and 15 feet 8 inches below the bottom of the masonry foundation. The water stands in this well permanently 2 feet 8 inches above its bottom. Three-fourths inch, soft copper rods led to the bottom of the well, which was filled to the masonry mentioned above with sand. The measured resistance of this earth connection was 2.2 ohms.[20] On several occasions lightning struck the Monument and followed the conductors provided for it to the bottom of the shaft, where it jumped to a plate in the floor, passing into the engine room and other places and doing considerable damage. Later a connection was made from the conductors in the bottom of the shaft to a water pipe in the motor room, with the result that a later stroke passed to earth with but slight damage and did not leave the conductors at any point. No further trouble has been experienced.

As pointed out above, the resistance and inductance of the system should be made as low as practicable. At first sight it might seem that too low a resistance could be obtained; that is, if the resistance were negligible, destructive oscillations in the rod might result from the impulse given by the lightning stroke. In practice, however, the chance of obtaining an effect of this kind through too little resistance in the ground connection need not be taken into consideration. On the contrary, the real difficulty in nearly all cases is that of getting a sufficiently low resistance.

10. METER SYSTEMS, SIGNAL SYSTEMS, AND AUXILIARY GROUND CONNECTIONS FOR TESTING PURPOSES

The use of ground connections for meter systems on high voltage lines is confined chiefly to preventing a rise of potential against ground of the meter circuits which may endanger the lives of attendants or injure the insulation. Such a rise of potential may occur either through electrostatic induction, or through failure of insulation in instrument transformers which permits the line voltage and current to enter the meter circuits. To guard against the first is not difficult. A ground connection of even rather high resistance, say several hundred ohms, will serve the purpose. To guard against the second, however, is not so easy. Here a low resistance of the ground connection is required, because in the event of a failure of insulation, there may be a heavy flow of current to earth. Connection to water pipes is especially to be recommended.

[20] Reports of Engineer Officers in Charge of Public Buildings and Grounds in Washington: 1885 to 1912.

Earth connections for signal systems often form part of the operating circuit, and for that reason special attention needs to be given to their resistance, more particularly, to the variation of the resistance with seasons. A signal system installed in summer might work in a satisfactory manner, but with freezing weather an increase of resistance of the ground connections would take place, possibly enough to render the system inoperative. In making the installation, therefore, care should be taken to allow for seasonal changes.

Auxiliary ground connections are frequently needed for testing purposes. The resistance and other electrical characteristics are here determined by the requirements of each case. In testing insulation, for example, the resistance of the ground connection may be very high—several thousand ohms need not be considered too high for good results—but for other purposes it may need to be low. A case in point is testing for the energy-absorbing capacity of ground connections for electrical circuits, which is taken up later under Section VI, "Inspection and Testing."

IV. DIFFERENT FORMS OF GROUND CONNECTIONS AND THE ELECTRICAL CHARACTERISTICS OF EACH

The different types of ground connections in common use may be enumerated as follows: (1) Driven pipes, (2) plates, (3) strips, (4) patented devices, and (5) water pipes. The electrical characteristics of each type and the extent of its suitability for grounding electrical systems are discussed below, patented devices being included under one head because, although there are many of them on the market, they are not fundamentally different from one another. Some space is also devoted to multiple ground connections.

1. DRIVEN PIPES

For many purposes driven pipes are economical and reasonably satisfactory, especially if the soil is deep and not so stony as to prevent driving them. They serve very well for lightning rods, lightning arresters, low-voltage circuits fed by transformers of small power rating where there is little likelihood of contact between high-voltage and low-voltage wires, and for other electrical circuits and apparatus which do not require a resistance to flow of current into the earth of less than a few ohms. Where very low resistances are required, however, they are, in general, not satis-

factory. Nevertheless, as compared with other types of grounds, they possess a marked advantage in that connection between pipe and ground wire can be made above the surface of the soil, enabling easy inspection; and they are renewable at relatively low cost. Moreover, the ground area required for an earth connection of this type is small, making for convenience in some places where excavation is out of the question because of restricted space, or pavements.

(*a*) VARIATION OF RESISTANCE WITH DEPTH.—This characteristic of driven pipes has been investigated heretofore by Creighton.[21] His results have been checked in this investigation, using 54 specimens of three-fourth inch galvanized iron pipe of lengths varying in steps of 1 foot up to 10 feet. These were driven in rather stony clay soil. Table 1 gives the number of specimens and the average of their measured resistances for each length. The measurements were made by means of the ammeter-voltmeter method, with alternating current at 60 cycles per second. A detailed description of this method is given further on in this paper under "Testing" in Section VI, 2 (*a*), (*b*), and (*c*). When the pipes were driven, the ground was very wet, and when the data given in Table 1 were obtained, they had been in place seven months, so there was ample opportunity for the soil to settle and eliminate disturbances due to driving. The values of resistance, however, are to be considered as having probable errors of 2 or 3 per cent because of fluctuations of voltage while readings were taken, which were due to varying loads on the line at other points.

TABLE 1.—Variation of Resistance of Driven Pipes with Depth[a]

Specimens	Depth in feet	$2l=L$ in centimeters	Capacity in electrostatic units	Average measured resistance	Calculated resistance, uniform soil
				Ohms	Ohms
8	1	61.0	7.92	167	149.3
8	2	122.0	13.45	76.3	87.8
8	3	183.0	18.52	47.2	63.8
8	4	244.0	23.35	37.5	50.6
8	5	304.0	28.00	49.5	42.3
1	6	366.0	32.40	42.5	36.5
3	7	427.0	36.85	31.0	32.1
1	8	488.0	41.20	22.5	28.7
1	9	549.0	45.40	23.5	26.0
8	10	610.0	49.60	36.5	23.8

[a] External diameter of pipes used in this test, 1.02 inches. $\rho = 7420$ ohms per cubic centimeter.

[21] General Electric Review, 15, pp. 15 and 66.

Referring to Table 1 it will be seen that the results of the measurements are very irregular; for instance, the average resistance to flow of current away from a group of pipes driven 10 feet into the ground is practically the same as for a group driven 4 feet. The resistances to flow of current away from individual specimens were also found to be very irregular, and in all cases the irregularities were much greater than those which could be attributed to errors in measurement. The soil, however, was found to be very nonhomogeneous, and it is undoubtedly to this that the larger part of the irregularities must be attributed. In fact, in driving it was discovered that the greater lengths of pipe penetrated a stratum which consisted of nearly all small bowlders of 2 to 5 inches in diameter. The resistivity of such bowlders is extremely high in comparison with that of soil and their presence tends to produce differences in resistances between specimens of the same kind on account of their nonuniform distribution. Because of these irregularities it would be more or less misleading to attempt to show the relation between resistance and depth by drawing a curve through the points representing the observed values, so a curve was constructed the shape of which would at least approximate that obtained by making observations on pipes driven in soil of uniform resistivity.

In constructing this curve use was made of the formula $R = \frac{\rho}{2\pi C}$, which was given under resistance of ground connections. In this formula R is the resistance to flow of current away from a ground connection, ρ the resistivity of the soil, and C the combined electrostatic capacity in free space of the electrode and its image above the surface of the ground, the surface of the ground being supposed in this case to lie in a plane at right angles to the axis of the pipe. There seems to be no available formula for the electrostatic capacity of a cylinder in free space, so in calculating C an approximation was made by using the formula for the capacity of an ellipsoid of revolution, assuming the axes of the ellipsoid to be equal to the length and external diameter, respectively, of the pipe. This formula, for an ellipsoid of revolution of which the length of the major axis is great in comparison with that of the minor axis, is $C = \frac{L}{2 \log_e \frac{2L}{d}}$, where L is the length of the major axis and d of the minor axis.

The image of a driven pipe above the surface of the ground would be another pipe of the same length l and external diameter d extending above the surface. The value of L is therefore equal to $2l$, since C refers to the combination of electrode and image. The ratio of major to minor axis for the lengths of pipe under consideration ranges from 24 to 240. Just what error arises from the use of this formula can not, of course, be told. Because of the method of cutting and driving, however, a pipe can be considered as a cylinder with rounded corners. Hence, it does not seem that the difference in capacity between a pipe of given length and diameter and an ellipsoid of revolution of which the major and minor axes corresponded, respectively, to the length and diameter of the pipe would be more than a few per cent. At any rate the method can be considered as a rough approximation and is the most convenient means at hand for smoothing out irregularities in the observations.

From the foregoing formula C has been calculated for the various lengths of pipe, the results being given in Table 1. Substituting in $\rho = 2\pi C R$, the value of ρ corresponding to each set of measurements is found. The average value of ρ for the 10 sets of measurements is 7420 ohms per cm [3], from which in turn has been calculated the resistance for each length of pipe as if the resistivity of the soil were uniform. These results are given in the last column of Table 1 and have been used to plot the curve in Fig. 11. The circles show where the points corresponding to the measured resistances fall and are about evenly distributed on either side of the curve. As stated above, this curve can be considered as only a rough approximation to the true curve, but nevertheless shows clearly how the resistance to flow of current away from a pipe driven in soil of uniform resistivity varies with the depth. Evidently not much is to be gained by driving pipes more than 10 feet after moist earth has been reached. As will be shown later, it is, in most cases, more economical to decrease the resistance by putting pipes in parallel than by driving deeper than 10 feet into conducting earth.

Since R depends directly upon ρ, the shape of the curve will be the same no matter what the resistivity may be; that is, if ρ_1 represents the resistivity corresponding to a given curve, and ρ_2 the resistivity corresponding to any other curve, the latter curve may be found by multiplying the ordinates of the given curve by $\frac{\rho_2}{\rho_1}$,

if the sizes and lengths of pipe concerned are the same in the two cases. Practically, however, the curve shows only what depth in conducting earth it is most desirable to attain with driven pipes.

(*b*) VARIATION OF RESISTANCE BETWEEN TWO DRIVEN PIPES WITH DEPTH AND DISTANCE APART.—For this experiment 40 specimens were used. As indicated in Table 2, where the results of the measurements are given, their lengths ranged from 2 to 10 feet and their distances apart from 6 inches to 25 feet. They were driven in the soil as described in the preceding section, the specimens in

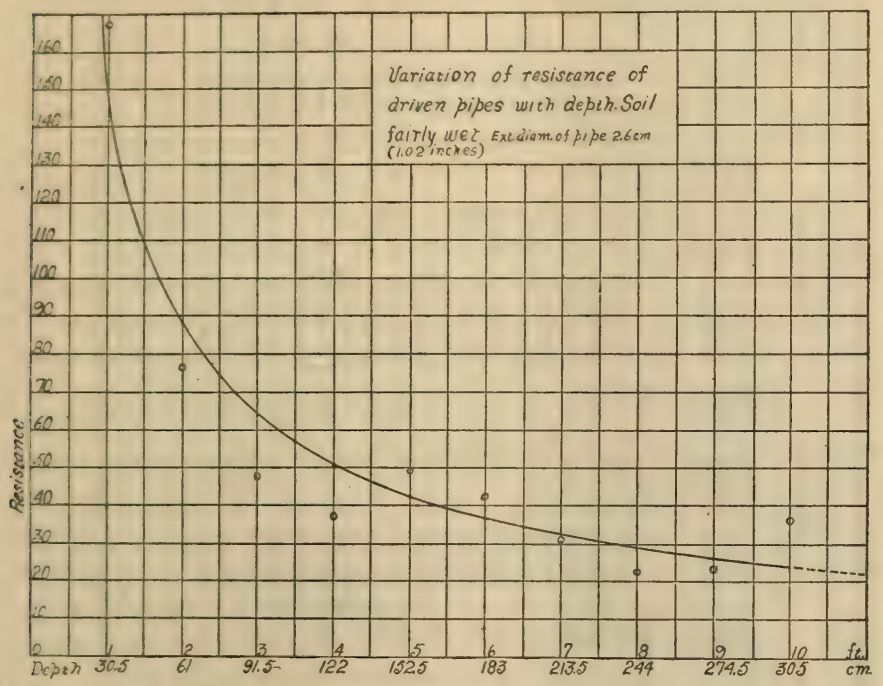


FIG. 11

the two cases, with certain exceptions, being, in fact, identical. The measurements were made by the ammeter voltmeter method. As stated heretofore, this method is described under "Testing" in Section VI, 2 (*a*), (*b*), and (*c*).

In this case, of course, irregularities in the results due to the non-homogeneity of the soil are present the same as in the preceding experiment. In order to draw a curve which will give a clear idea of the way in which the resistance to flow of current from one pipe to another varies with the distance between them, it is therefore necessary to eliminate these irregularities. As previously shown, it is possible to calculate from $R = \frac{\rho}{2\pi C}$ the

TABLE 2.—Variation of Resistance Between Driven Pipes With Distance Apart[a]

Resistance of each specimen				Distance apart	Depth, 2 feet			Depth, 3 feet			Depth, 4 feet			Depth, 5 feet			Depth, 10 feet		
No.	Resistance	No.	Resistance		Specimens in series	Measured resistance	Calculated resistance	Specimens in series	Measured resistance	Calculated resistance	Specimens in series	Measured resistance	Calculated resistance	Specimens in series	Measured resistance	Calculated resistance	Specimens in series	Measured resistance	Calculated resistance
	Ohms		Ohms	Feet		Ohms	Ohms		Ohms	Ohms		Ohms	Ohms		Ohms	Ohms		Ohms	Ohms
66	127	99	54	0.5	75–76	164	161	112–113	96	84	105–106	59	59	82–83	74	76	98– 99	52	54
67	57	100	51	1	76–77	187	185	113–114	110	101	106–107	84	77	83–84	93	87	99–100	64	69
68	44	101	59	2	77–78	216	214	114–115	120	117	107–108	99	91	84–85	131	118	100–101	74	76
69	62	102	65	3	78–79	217	221	115–116	127	125	106-108	98	94	83–85	139	124	99–101	90	86
74	42	103	65	3	76–78			113–115			108–109			85–86			101–102		
75	125	104	61	4	79–80	224	225	116–117	126	129	109–110	100	98	86–87	144	133	102–103	104	90
76	125	105	60	5	77–79	215	229	114–116	134	134	107–109	118	105	84–86	157	135	100–102	96	94
77	123	106	61	6	80–81	227	232	117–118	137	136	106–109	106	104	83–86	131	132	99–102	105	96
78	125	107	70	6	76–79			113–116			110–111			87–88			103–104		
79	108	108	61	7	78–80	255	239	115–117	137	137	108–110	104	105	85–87	141	136	101–103	109	99
80	137	109	65	9	77–80	256	242	114–117	145	140	107–110	117	110	84–87	144	140	100–103	104	101
81	110	110	58	10	81–66	231	238	118– 67	134	141	111– 68	105	108	88–69	129	137	104– 74	105	102
82	69	111	59	10	79–81			116–118			109–111			86–88			102–104		
83	76	112	88	10	76–80			113–117			106–110			83–87			99–103		
84	82	113	84	13	78–81	231	242	115–118	140	143	108–111	111	110	85–88	134	140	101–104	112	105
85	83	114	80	15	77–81	231	243	114–118	146	145	107–111	121	111	84–88	136	143	100–104	104	105
86	90	115	75	20	79–66	231	243	116– 67	123	144	109– 68	103	113	86–69	148	144	102– 74	102	108
87	71	116	71	25	77–66	252	248	114– 67	132	145	107– 68	110	115	84–69	141	145	100– 74	89	108
88	59	117	76																
98	54	118	72																

[a] Where more than one pair of electrodes were available at any given distance apart, average results were used in tabulation and in plotting curves.

resistance to flow of current from one electrode to another if ρ and C are known, ρ being the resistivity of the soil and C the electrostatic capacity of the condenser formed by one of the electrodes and its image above the surface of the ground, on the one hand, and the other electrode and its image on the other hand. If C were known for the different lengths of pipe and their distances apart, an average value of ρ could be obtained, from which, in turn, could be calculated the different values of R as if the resistivity of the soil were uniform throughout. At present there seems, however, to be no available formula for calculating the value of C in the case of pipes, so it was necessary to resort to a less desirable means of eliminating irregularities, a method which, in fact, eliminates irregularities with a fair degree of approximation between measurements on pipes of the same length, but not between groups of different lengths.

As previously indicated, the resistance to flow of current from one electrode to another, as well as away from a single electrode, depends directly upon the resistivity of the soil. Suppose that R_1, R_2, $R_3 \cdots R_n$ are the measured resistances to flow of current away from each pipe of a group of the same length driven at different distances from each other. Then $R_{av} = \frac{R_1 + R_2 + R_3 + \cdots R_n}{n}$ is the resistance which each would have if the resistivity of the soil were everywhere equal to ρ_{av}. Let R' be the measured resistance to flow of current from any one of the driven pipes to another, say from (1) to (2); R' will correspond to a resistivity of the soil everywhere equal to ρ'. In order to reduce R' to a value R which it would have if the resistivity of the soil were everywhere equal to ρ_{av}, it is only necessary to put $R = \frac{\rho_{av}}{\rho'} R'$. The value of ρ' must be determined, however, before use can be made of the formula. If the pipes are at an infinite distance from each other, it is evident that $\rho' = \frac{\rho_1 + \rho_2}{2}$ where ρ_1 and ρ_2 are the values of resistivity corresponding to R_1 and R_2. Then $R = \frac{2\ \rho_{av}}{\rho_1 + \rho_2} R' = \frac{2R_{av}}{R_1 + R_2} R'$, since $\frac{2\ \rho_{av}}{\rho_1 + \rho_2} = \frac{2R_{av}}{R_1 + R_2}$. This holds exactly for pipes driven at a great distance from each other, but when they are brought close together the formula is only an approximation. However, because of the fact that it is the soil in the immediate vicinity of the electrode which has the greatest effect in producing resistance, the error becomes appreciable only when the electrodes are very near each other.

The results of Table 2 have been reduced in accordance with this formula, and curves corresponding to groups of pipes 2 feet, 5 feet, and 10 feet lengths are shown in Fig. 12. The circles and dots represent the observed values of resistance and seem more or less evenly distributed on either side of their respective curves. As the distance between the pipes increases the ordinate of the curve approaches a constant value, $2 R_{av}$, rapidly at first and then more slowly, reaching its maximum at an infinite distance. At 10

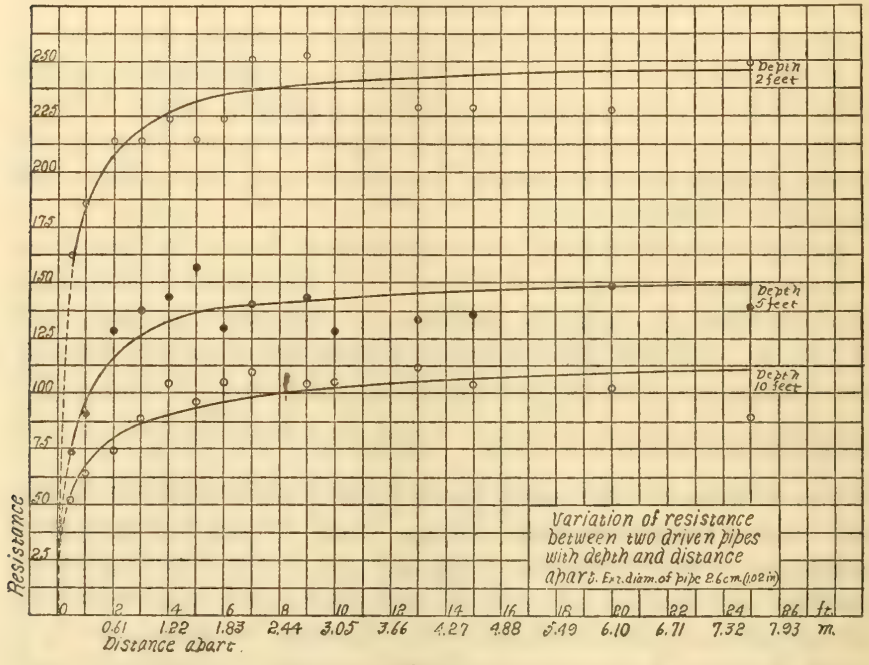


FIG. 12

feet, however, the remaining increase of resistance is in most practical cases negligible.

The foregoing method of eliminating irregularities takes no account of differences between groups, so those of 3 and 4 feet length have been omitted from Fig. 12, for the reason that the curves representing these groups would nearly coincide with some of the others. As in Table 1, the results of Table 2 have probable errors of 2 or 3 per cent because of fluctuations of line voltage while readings were being taken.

(*c*) VARIATION OF RESISTANCE OF TWO AND MORE PIPES IN PARALLEL WITH DISTANCE APART AND DEPTH. The first measurements of this series were made on the ¾-inch galvanized-iron pipe specimens previously described. Two specimens of each

group were connected and the resistance to flow of current away from them measured by the ammeter-voltmeter method. This was done for each pair of specimens in each group. The results are given in Table 3, the irregularities having been eliminated in much the same way as under (*b*); for if two pipes are in parallel and at

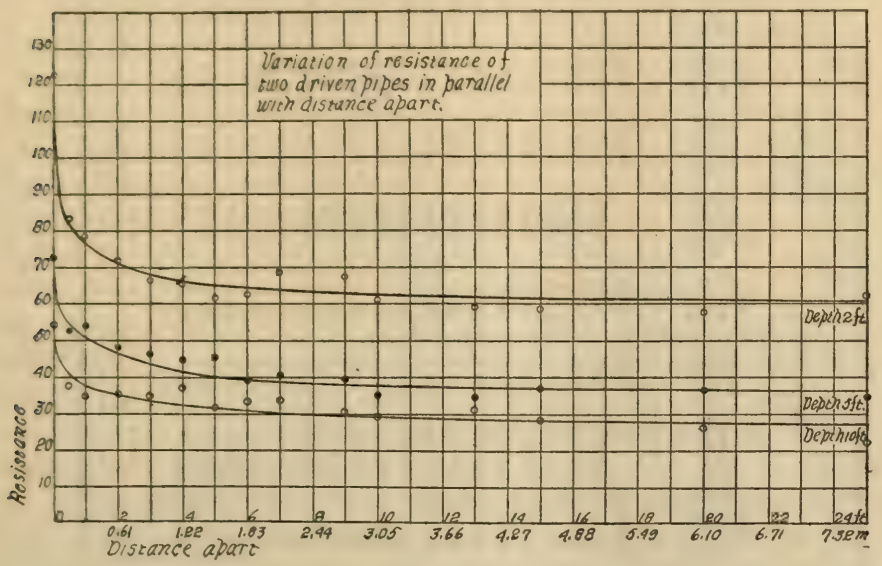


FIG. 13

a great distance from each other, the combined resistance to flow of current away from them may be expressed by $R'' = \frac{R_1 R_2}{R_1 + R_2}$, the well-known formula for the resistance of conductors in parallel, in which R_1 and R_2 are the measured resistances to flow of current away from each of the pipes. Moreover, if the soil were everywhere of resistivity ρ, $_{av} R''$ would be equal to $\frac{R_{av}}{2}$. Hence, as in the preceding section, $R = \frac{\rho_{av}}{\rho''} R'' = \frac{R_{av}(R_1 + R_2)}{2 R_1 R_2} R''$, since $\frac{R_{av}}{2}$ and $\frac{R_1 R_2}{R_1 + R_2}$ are proportional to ρav and ρ'', respectively. This formula is exact when the pipes are at a great distance from each other and does not introduce an appreciable error unless they are quite close together. The results for the groups of 2 feet, 5 feet, and 10 feet lengths are plotted in Fig. 13, the curves representing the corrected values of resistance and the circles and dots the observed values. At zero distance the resistance is taken to be the average of all of the specimens in the group.

TABLE 3.—Variation of Resistance of Two Pipes in Parallel With Distance Apart and Depth [a]

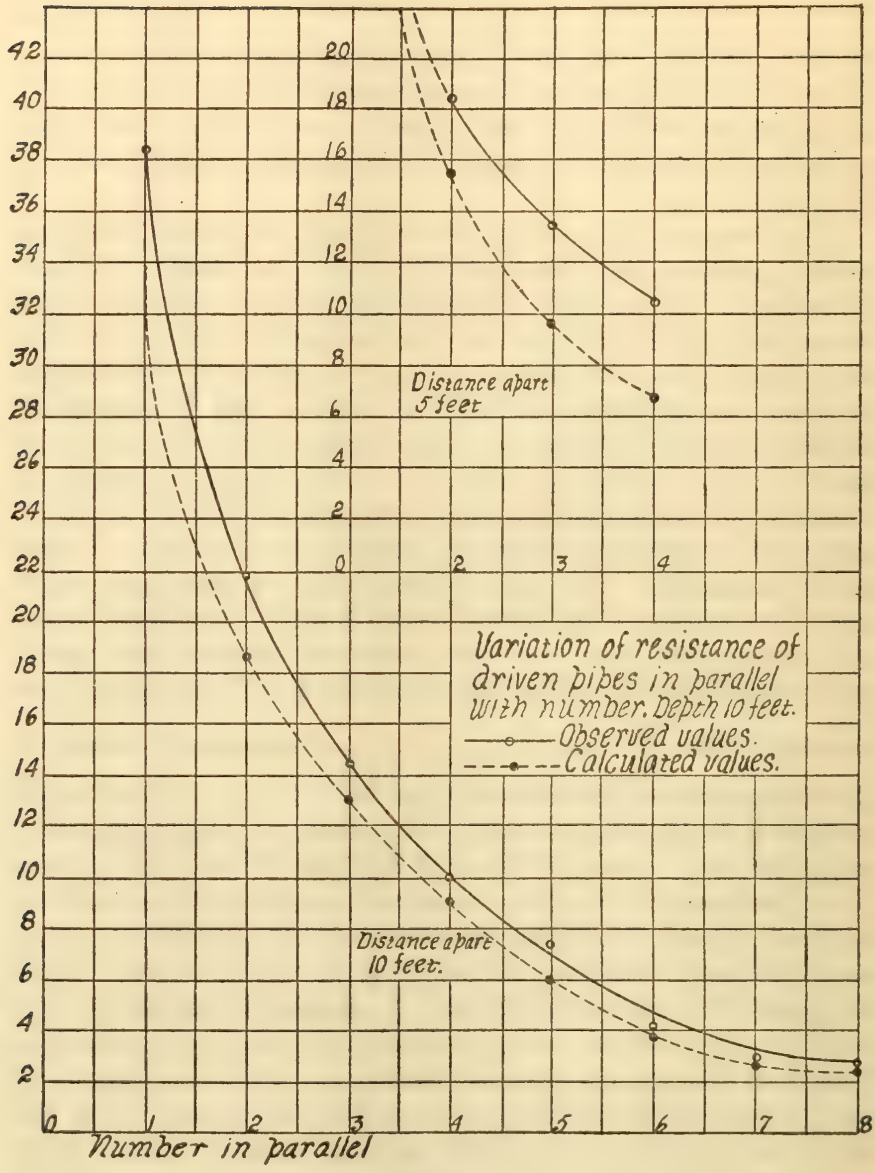
Resistance of each specimen.				Distance apart	Depth, 2 feet			Depth, 3 feet			Depth, 4 feet			Depth, 5 feet			Depth, 10 feet		
No.	Resistance	No.	Resistance		Specimens in parallel	Measured resistance	Calculated resistance	Specimens in parallel	Measured resistance	Calculated resistance	Specimens in parallel	Measured resistance	Calculated resistance	Specimens in parallel	Measured resistance	Calculated resistance	Specimens in parallel	Measured resistance	Calculated resistance
	Ohms		Ohms	Feet		Ohms	Ohms		Ohms	Ohms		Ohms	Ohms		Ohms	Ohms		Ohms	Ohms
66	127.3	99	51.9	0.5	75–76	83.8	82.2	112–113	60.8	53.2	105–106	44.0	43.3	82–83	52.9	54.5	98– 99	37.8	40.4
67	54.2	100	49.5	1	76–77	79.1	77.6	113–114	53.5	49.3	106–107	42.6	38.9	83–84	54.5	51.3	99–100	34.7	37.5
68	42.6	101	58.4	2	77–78	72.4	71.1	114–115	45.7	44.4	107–108	39.1	35.9	84–85	48.7	43.6	100–101	35.2	35.9
69	61.2	102	63.1	3	78–79	64.6	68.8	115–116	42.2	43.4	108–109	36.5	34.6	85–86	48.3	41.0	102–102	36.6	33.0
74	40.4	103	63.6	3	76–78	69.4	67.7	113–115	44.8	42.4	106–108	35.3	34.6	83–85	45.3	42.3	99–101	33.6	33.5
75	124.9	104	60.0	4	79–80	66.1	67.0	116–117	41.0	42.0	109–110	34.9	33.9	86–87	44.9	41.3	102–103	37.5	32.5
76	126.6	105	58.8	5	77–79	61.9	66.7	114–116	40.7	40.5	107–109	36.7	32.4	84–86	46.1	39.4	100–102	31.9	31.5
77	124.9	106	59.4	6	80–81	64.7	64.8	117–118	39.6	40.2	106–109	33.9	32.1	83–86	43.8	39.1	99–102	31.9	30.6
78	126.4	107	68.3	6	76–79	61.2	65.1	113–116	41.0	40.0	110–111	31.7	32.4	87–88	34.7	40.4	103–104	34.9	30.9
79	107.0	108	59.1	7	78–80	69.3	64.1	115–117	39.9	39.8	108–110	32.0	32.2	85–87	40.7	39.2	101–103	33.8	30.3
80	141.5	109	63.3	9	77–80	68.2	63.4	114–117	40.4	39.1	107–110	33.0	31.0	84–87	39.8	38.5	100–103	30.3	29.8
81	109.0	110	56.4	10	81–66	60.5	63.5	118– 67	32.9	39.4	111– 68	26.6	31.7	88–69	31.3	38.7	104– 74	26.0	29.4
82	67.7	111	57.2	10	79–81	56.2	64.2	116–118	36.9	38.7	109–111	32.2	31.0	86–88	36.7	38.4	102–104	33.0	29.4
83	74.6	112	86.0	10	76–80	67.9	62.8	113–117	41.2	38.8	106–110	30.9	31.0	83–87	37.9	38.1	99–103	30.6	29.3
84	81.1	113	82.0	13	78–81	59.6	62.8	115–118	37.3	38.1	108–111	30.7	30.7	85–88	34.9	38.0	101–104	31.3	29.0
85	82.0	114	78.0	15	77–81	59.0	62.5	114–118	37.9	37.5	107–111	32.4	30.0	84–88	37.6	.....	100–104	28.5	28.7
86	90.4	115	73.3	20	79–66	58.2	61.7	116– 67	31.3	37.8	109– 68	26.3	30.0	86–69	36.7	36.8	102– 74	25.4	28.2
87	70.6	116	69.5	25	77–66	62.7	61.3	114– 67	34.2	38.0	107– 68	26.8	29.7	84–69	35.1	36.8	100– 74	22.6	27.5
88	56.9	117	74.1	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
98	50.4	118	70.7	.....	[b] 123.4	.....	.....	[b] 73.5	.....	.....	[b] 58.1	.....	.....	[b] 73.1	.....	.....	[b] 54.7	.....	.....

[a] In cases where more than one pair of electrodes were available at any given distance apart, the average results were used in plotting the curves.

[b] Average resistance of specimens in each group.

The curves show that as the distance between the pipes increases the resistance decreases, rapidly at first and then more slowly, tending toward a value $\frac{R_{av}}{2}$ at infinity. After 6 feet is reached, however, the rate of decrease becomes very slow and, in fact from 6 to 10 feet becomes practically negligible. At 6 feet apart the resistance of two pipes in parallel is approximately 55 per cent of one of them and at 2 feet apart is approximately 65 per cent.

It is desirable to know whether these approximate relations between number and resistance hold when the number of pipes is increased. Accordingly, eight specimens 10 feet in length were driven in a row 10 feet apart and the resistance to flow of current away from them measured singly and in parallel. The results of these measurements are given in Table 4, also the results of measurements on four pipes 10 feet in length driven in a row 5 feet apart. In the table the second column gives the measured resistance of each specimen, the fourth the resistance to flow of current away from specimens (1) and (2); (1), (2), and (3); and so on, in parallel. The fifth column gives the resistance which each combination of specimens would have if they were so far away from each other that their respective electric fields would not interfere; that is, at an infinite distance. These values were calculated from $\frac{1}{R}=\frac{1}{R_1}+\frac{1}{R_2}+\frac{1}{R_3}+\cdots+\frac{1}{R_n}$, the familiar formula for the conductance of conductors in parallel. In Fig. 14 the results are shown in the form of a curve, the dotted-line curves representing calculated values and the full-line curves measured values. At 10 feet apart it is evident that the number of pipes could be extended almost indefinitely and the ratio of calculated to measured resistance would not be less than 80 or 90 per cent. At 5 feet apart the ratio of calculated to measured resistance is only 60 or 70 per cent, the curve indicating that this percentage decreases as the number of pipes increases. At 10 feet apart the ratio is practically constant as far as the curve goes. It is not likely that it would be practicable in many cases to drive a row of pipes of greater length than 70 feet, so the curve was not carried further. The steepness of the curve depends upon the distance apart of the pipes. For a row of given length, however, the greater the number the less the resistance.


42
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2
0
20
18
16
14
12
10
8
6
4
2
0
2
3
4
Distance apart 5 feet
Variation of resistance of driven pipes in parallel with number. Depth 10 feet.
Observed values.
Calculated values.
Distance apart 10 feet.
0
1
2
3
4
5
6
7
8
Number in parallel

FIG. 14

TABLE 4.—Variation of Resistance of Driven Pipes in Parallel With Number

Specimens	Resistance[a]	Specimens in parallel	Measured resistance	Calculated resistance
	PIPES 10 FEET APART			
	Ohms		Ohms	Ohms
1	30.3	1,2	19.8	18.4
2	47.1	1,2,3	14.4	13.2
3	45.9	1,2,3,4	10.0	9.1
4	29.1	1,2,3,4,5	7.4	5.9
5	17.0	1,6	4.1	3.7
6	9.9	1,7	2.9	2.7
7	9.7	1,8	2.7	2.5
8	39.7			
	PIPES 5 FEET APART			
9	34.5	9,10	18.2	15.0
10	26.0	9,11	13.5	9.6
11	27.6	9,12	10.8	7.2
12	28.5			

[a]Average of numbers 1 and 2=38.7.

In some instances it is necessary to make the resistance of an earth connection as small as practicable, but space is lacking in which to drive pipes at some distance from each other. This may be the case near telephone and power poles. Referring to Fig. 13, it is seen that the first foot or so of separation between a pair of pipes has the greatest influence in reducing the resistance to flow of current. Hence, much can be accomplished by driving two or more pipes even as close as 1 foot or so from each other. This is especially to be recommended as a course to follow when pipes are driven alongside of poles. Where a single pipe is driven beside a pole and close to it, the pole, which in most cases is of much greater resistivity than the soil, shuts off a large part of the current flow, unless the pipe extends some distance below the bottom of the pole. By driving another pipe on the opposite side, the resistance to flow of current can be considerably reduced. A particular instance may be cited in which three pipes 8 feet in length were driven equidistant from one another around a pole set about 4.5 feet in the ground. Measurements of resistance gave results as shown in Table 5. These results indicate that two pipes driven on opposite sides of a pole will give a resistance of approximately 65 per cent, and three pipes at 120 degrees apart approximately 53 per cent, of that of a single pipe. It is not likely, however, that a further increase in the number of pipes would produce an additional decrease in resistance sufficient to justify the expense of driving.

TABLE 5.—Resistance of Pipes Driven Around a Pole

Specimens	Resistance of each ground	Specimens in parallel	Resistance in parallel
	Ohms		Ohms
1	53.3	1-2	34.0
2	54.1	1-2-3	28.0
3	48.0	.....	.....

(*d*) VARIATION OF RESISTANCE WITH CONTACT AREA.—The specimens used for this experiment consisted of four 0.75-inch pipes, and three each of 1.25-inch, 2-inch, and 2.5-inch pipes, respectively, driven to a depth of 10 feet. The measurements, the results of which are given in Table 6, were made in the same manner as those previously recorded. On account of the nonuniformity of the soil, however, the results are so irregular as to give very little indication of the way in which the resistance would vary with contact area if the soil were uniform.

From this table it appears that the resistance to flow of current away from a 2.5-inch pipe is nearly as great as from a 1.25-inch pipe. This, of course, is not the case, at least not to the extent indicated by the observed values. A clearer idea of the variation of resistance with size of pipe may be obtained by making use of the observation equation $R=\frac{\rho}{2\pi C}$ as in some of the previous work, than by comparing the observed values themselves. As stated heretofore, R is the resistance to flow of current away from the electrode, ρ the resistivity of the soil, and C the electrostatic capacity in free space of the pipe and its image above the surface of the ground.

TABLE 6.—Variation of Resistance of Driven Pipes With Contact Area [a]

Specimens of each size	Size of pipe, internal diameter	External diameter of pipe	Electrostatic capacity	Average resistance	Calculated resistance
	Inches	Centimeters		Ohms	Ohms
.....	.....	0.5	39.1	(b)	40.2
.....	.....	1.0	43.6	(b)	36.1
.....	.....	1.5	45.5	(b)	34.5
.....	.....	2.0	47.7	(b)	32.9
4	0.75	2.6	49.6	38	31.7
3	1.25	4.2	53.8	26	29.2
3	2.0	6.0	57.3	27	27.4
3	2.5	7.3	59.6	24.5	26.4

a Depth—10 feet. b No observations.

In Table 6 are given the values of C for the different sizes of pipe on which measurements were taken and also for smaller sizes to enable extending the curve back toward the axis of ordinates. In calculating C the formula for an ellipsoid of revolution, $C = \frac{L}{2 \log_\epsilon \frac{2L}{d}}$, was taken as the nearest obtainable approximation to the real value in the same way as under (*a*) where variation of resistance with depth was discussed. Substituting the measured

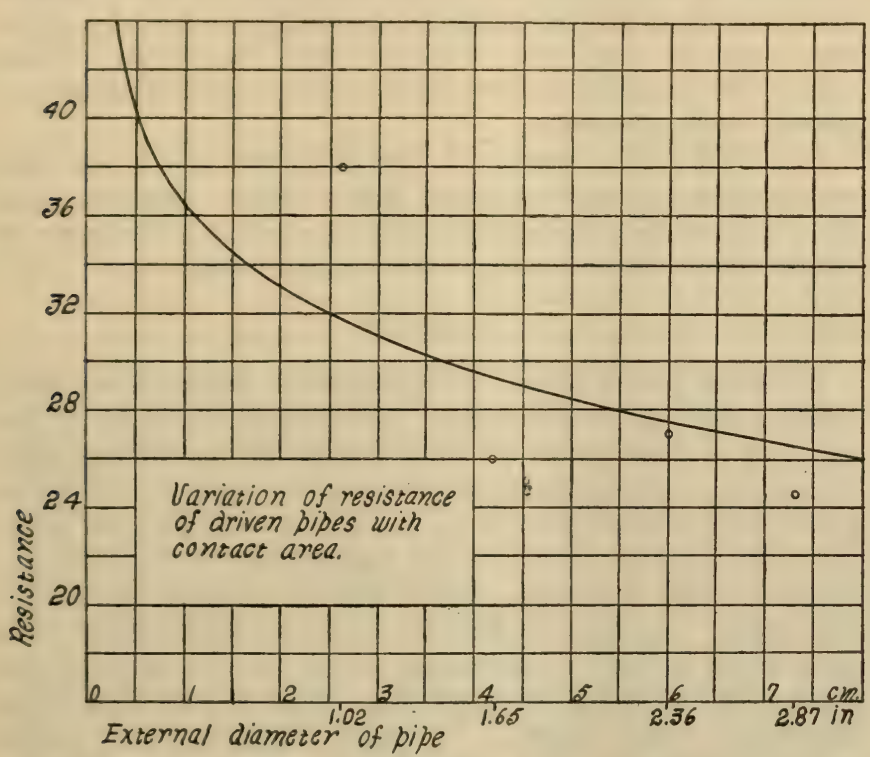

FIG. 15

values of resistance and corresponding values of C in $\rho = 2\pi CR$, the average value of ρ is found to be 9870 ohms per cm³. From this, in turn, the resistance for each size of pipe is calculated as if the resistivity of the soil were uniform. These calculated values of resistance are given in the last column of Table 6 and have been used to plot the curve of Fig. 15. The circles represent the observed values of resistance, the distance of the point above the curve being practically equal to the sum of the distances of the three points below the curve. The curve may, therefore, be taken

as a fair indication of the results which would be obtained in uniform soil, and shows that as the diameter of the pipe, and consequently the area of contact, increases the resistance decreases at a steadily decreasing rate. For instance, increasing the external diameter of the pipe from 1 to 2 cm (0.394 to 0.787 inch) decreases the resistance 9.34 per cent, from 2 to 3 cm (0.787 to 1.18 inches), 5.88 per cent, from 3 to 4 cm (1.18 to 1.57 inches), 4.84 per cent, and so on. Doubling the diameter or increasing it from 1 to 2 cm, 2 to 4 cm, and 4 to 8 cm (0.394 to 0.787 inch, 0.787 to 1.57 inches, and 1.57 to 3.15 inches) cause decreases of resistance of 9.34 per cent, 10.6 per cent, and 11.85 per cent, respectively. These values have been checked experimentally by other investigators, notably by Creighton.[22]

In driving pipes, therefore, it does not seem wise to use sizes smaller than 0.75 inch nor larger than 2 inches. Between these limits mechanical considerations determine whether the larger or smaller sizes should be used, as will be shown later.

2. PLATES

The use of buried plates for the purpose of grounding electrical systems seems to be decreasing. This is due, no doubt, to the fact that in most places the same results can be obtained with driven pipes as with plates, and at much less expense. Nevertheless, it may in some cases be necessary or advisable to use them, and it is, therefore, of interest to discuss their electrical characteristics. The discussion which follows, however, is largely theoretical. It would be desirable to obtain experimental data upon which to base the discussion, but in the case of plates the expense of obtaining consistent data seems greater than their importance would justify. To obtain consistent data would require observations on a great many specimens, since there is no practicable way of eliminating irregularities due to nonhomogeneity of the soil except by taking the average of a large number of measurements. In this investigation, therefore, the number of plates buried was limited to 12, of different sizes, which were put down mainly for the purpose of determining the variation of resistance with seasons and the effects of coke and salt.

(*a*) Variation of Resistance with Depth.—If a circular thin metal plate is embedded in the surface of the ground to a depth

[22] General Electric Review, 15, pp. 15 and 66.

equal to one-half its thickness, the resistance to flow of current away from it can be expressed by $R=\frac{\rho}{2\pi C}$, where ρ is the resistivity of the soil and C is the electrostatic capacity in free space of the plate. In this case $C=\frac{d}{\pi}$, where d is the diameter. If, now, the plate is sunk below the surface of the ground, the value of C which must be used in the formula for R is that of the combination of the plate and its image.[23] When the plate is so far beneath the surface that its image may be considered as at an infinite distance away from it, C becomes equal to $\frac{2d}{\pi}$. In passing from the surface of the ground to a great depth, therefore, the resistance to flow of current away from the plate changes from $R=\frac{\rho}{2d}$ to $R=\frac{\rho}{4d}$. This holds for a plate of any shape—that is, the resistance at the surface of the ground is twice that at a great depth, if the resistivity of the soil is uniform—and the shape of the curve showing variation of resistance with depth would be something like that of the curves in Fig. 13, showing variation of resistance of two driven pipes in parallel with distance apart, because the rate of change of C with increasing distance would be much the same. At least, R would decrease rapidly with the first few feet increase in depth and then more slowly, approaching a constant value at an infinite depth. Hence, for plates of ordinary size—that is, of areas from 10 to 20 square feet—the depth in conducting soil should be from 5 to 8 feet, since the curves of Fig. 13 indicate that greater depths would not show a further marked decrease of resistance. In fact, for a plate or other electrode of any size or shape, when the depth is such as to make the distance between the electrode and its image several times the dimensions of the electrode, increasing the depth will not result in a further marked decrease of resistance, because at those distances the rate of increase of C with increase of distance becomes very slow.

(*b*) Variation of Resistance with Area of Plate.—Referring again to the example of the circular plate embedded in the surface of the ground, it will be seen that the resistance to flow of current away from it varies inversely as the diameter; that is, doubling

[23] See Appendix III.

the diameter, and thus quadrupling the area of such a plate, halves the resistance. On the other hand, for a plate of rectangular shape which is very long in comparison with its width, quadrupling the area by increasing the length much more than halves the resistance. A particular instance may be given in which increasing the length of a buried strip of metal 1.5 inches wide from 40 feet to 160 feet reduced the resistance from 9.6 to 3.3 ohms. For rectangular plates of which the width is one-third to one-half the length, however, the case of the circular plate more nearly represents the conditions; i. e., quadrupling the area by a proportional increase of dimensions practically halves the resistance. This relationship between area and resistance is indicated by the fact that measurements on plates buried near other other showed resistances as follows: (1) Average resistance of two plates 2 feet by 4 feet buried 5 feet deep, 32.5 ohms; (2) resistance of one plate 2 feet by 8 feet buried 4 feet deep, 24.5 ohms; (3) resistance of one plate 4 feet by 8 feet buried 4 feet deep, 17.5 ohms. Because of the nonhomogeneity of the soil, however, these data must be taken only as indicating the relationship mentioned above and not as a check upon it.

To gain an idea of the rate at which resistance to flow of current away from a plate decreases with increasing size, the curve shown in Fig. 16 is given. This curve represents values calculated from the formula $R=\frac{\rho}{2d}=\frac{\rho}{4}\sqrt{\frac{\pi}{A}}$, where A is the area of the circular plate. The value of ρ in this case is assumed to be 7000 ohms per cubic centimeter, or very nearly the value found in one or two cases of driven pipes previously given. This curve shows that when a circular plate embedded in the surface of the ground reaches an area of 20 or 30 square feet the rate of decrease of resistance with increasing area becomes very slow. This represents, roughly, the conditions for a plate of rectangular shape beneath the surface, so it appears that the area of a single plate can not economically be increased beyond these dimensions. As indicated below, it requires much less labor and material to bury two small plates at a distance from each other and connect them by a heavy wire than to bury a single large plate which will have the same resistance to flow of current away from it into the earth as the two small plates in parallel.

(*c*) Resistance of Two Plates in Parallel.—In this case measurements were made on five plates 2 feet by 4 feet in size,

which were buried at different distances from one another in rather stony clay soil. They were laid in a row with distances between ends as indicated in Table 7, where the results of the measurements are given. Nos. 32, 33, and 36 were buried on edge in trenches 6 feet deep; Nos. 34 and 35 were buried flat in holes 5 feet deep. The center lines of those on edge were therefore at the same depth as the plane of those which were laid flat.

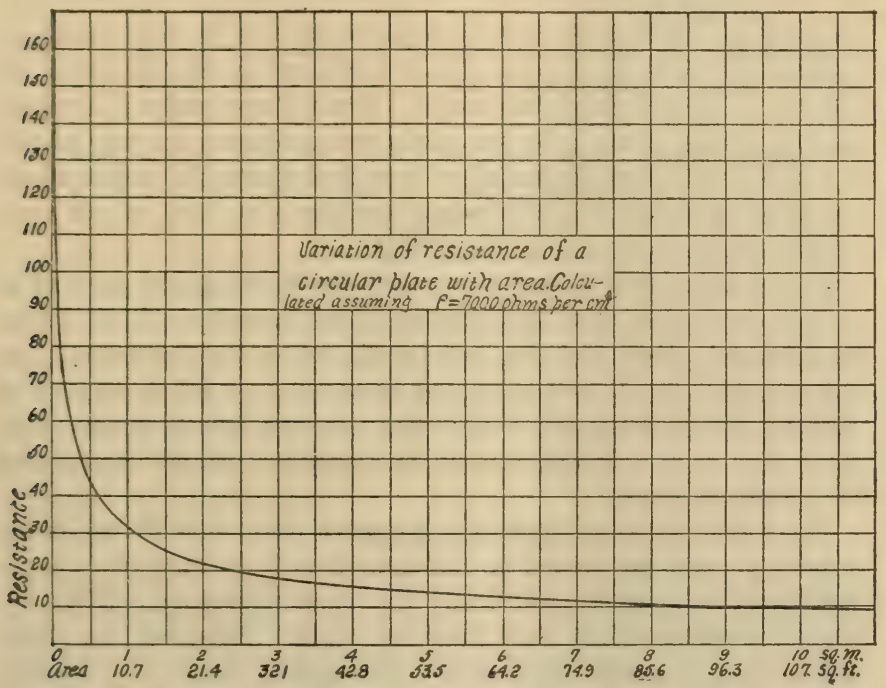

FIG. 16

The measurements of resistance were made by means of the ammeter-voltmeter method.

TABLE 7.—Resistance of Two Plates in Parallel

Plates	Resistance	Plates in parallel	Distance between ends	Measured resistance	Calculated resistance	Ratio of calculated to measured resistance
	Ohms		Feet	Ohms	Ohms	Per cent
32	31.2	32–33	1	18.8	14.5	77.2
33	27.2	33–34	5	16.1	13.6	84.4
34	27.4	32–34	10	16.2	14.5	90.0
35	44.3	32–35	29	18.7	18.3	97.8
36	31.6	35–36	30	18.6	18.4	99.0

The resistance of each specimen was first measured and then the resistances of the different pairs in parallel. From the results of the measurements on each specimen have been calculated the resistances which the different pairs in parallel would have if they were at an infinite distance apart. These values were obtained by applying the formula for the resistance of conductors in parallel, or $R=\frac{R_1 R_2}{R_1+R_2}$, R_1 and R_2 being the resistances of the individual specimens. The results of these calculations are given in the sixth column of Table 7. In the last column are given the ratios of calculated to measured resistances. From these ratios it appears that to obtain practically the minimum resistance for two plates in parallel they must be placed 25 or 30 feet apart. At 10 feet apart the ratio of calculated to measured resistance is about 90 per cent and at 1 foot apart about 77 per cent.

It has been stated heretofore that quadrupling the area of a rectangular plate, say, by increasing the dimensions from 2 feet by 4 feet to 4 feet by 8 feet, practically halves the resistance. In the case of Nos. 32 and 33 it will be noted that if the area were doubled by doubling the length and the two halves of the plate were then moved 1 foot apart, the resistance would be reduced by about one-third.

From the foregoing discussion it seems, then, that if two plates 2 feet by 4 feet are buried in uniform soil at a distance of 25 to 30 feet from each other, practically the same resistance will be obtained as with a single plate 4 feet by 8 feet. Moreover, the excavation and material required for the smaller plates will be but little more than half that for the larger plate. To bury a number of small plates would, of course, require considerable ground space, and where this is not available it would be impracticable; but where space is available, the required conductance can be more economically obtained with the small plates in parallel than with a single large one. It should be stated that the sizes of the small plates here referred to approximate 20 to 30 square feet. Up to that size it is economical to increase the area of the plate in order to decrease the resistance. When less resistance is required than these sizes will give, however, economy lies in an increased number of plates.

(*d*) Plates on Edge v. Plates Laid Flat.—In some cases it may be more advantageous to bury plates on edge than flat. In the first place, if the width of the plate is more than 2 feet less excavation may be required, because the trench need only be

wide enough to work in. It should be deep enough, however, to give an average depth equal to the depth which would be given if the plates were laid flat. In the second place, when a plate is placed on edge better contact can be made, usually, with the ground. In filling the trench the earth can be rammed on both sides of the plate, making good contact over the entire surface. On the other hand when a plate is laid flat it may rest on humps in the bottom of the trench and prevent good contact with the ground at all points. This is a condition which is very difficult to avoid. It is likely, however, that after a plate has been in place for some time, settlement will take place to a sufficient extent to eliminate the humps, unless the ground is very hard or stony. Nevertheless, to have good contact from the start is very desirable.

In the course of this investigation measurements were made on several plates, part of which were laid flat and part on edge. In the case of those laid flat there appeared to be a tendency for the resistance to be higher at the start than in the case of those on edge, with considerable decreases in the first few months, indicating settling as pointed out above. On the other hand, after settlement had taken place, there was no indication of a marked difference of resistance that could not be attributed to the non-homogeneity of the soil.

3. STRIPS

Where bedrock is near the surface of the ground, it is in many cases out of the question to drive pipes or to dig deep enough to make an effective ground connection with plates. Moreover, the ground in such places is likely to be very dry, particularly during periods when there is little rain, for there is but slight opportunity for storage of moisture deep in the ground during wet seasons to be absorbed by the surface strata through capillary action when periods of drought occur. The best procedure under such circumstances is to connect to earth by burying narrow strips of metal in trenches dug as deep as the rock layer will allow. Because of the high resistivity of the soil which is encountered in dry seasons, it is necessary to have a ground connection of considerable extent, and metal in the form of narrow strips offers the most efficient means of obtaining it. This is shown by the fact that for a given amount of metal the strip form can be made to give a greater value of the electrostatic capacity, and hence a lower value of resistance, than any other, as mentioned under "Resistance of ground connections," Section II.

The use of buried strips is most likely to be necessary in the case of lightning-rod systems, but may be made to serve any purpose for which a ground connection may be required. For lightning rods, however, this type of ground connection is very desirable where the soil is shallow, and it may be said further that its use in soils of high resistivity will be found advantageous whether the conditions are such as to prevent the use of driven pipes or not. Its desirability in this case, especially if a considerable network of strips is used around a building, arises from the facility with

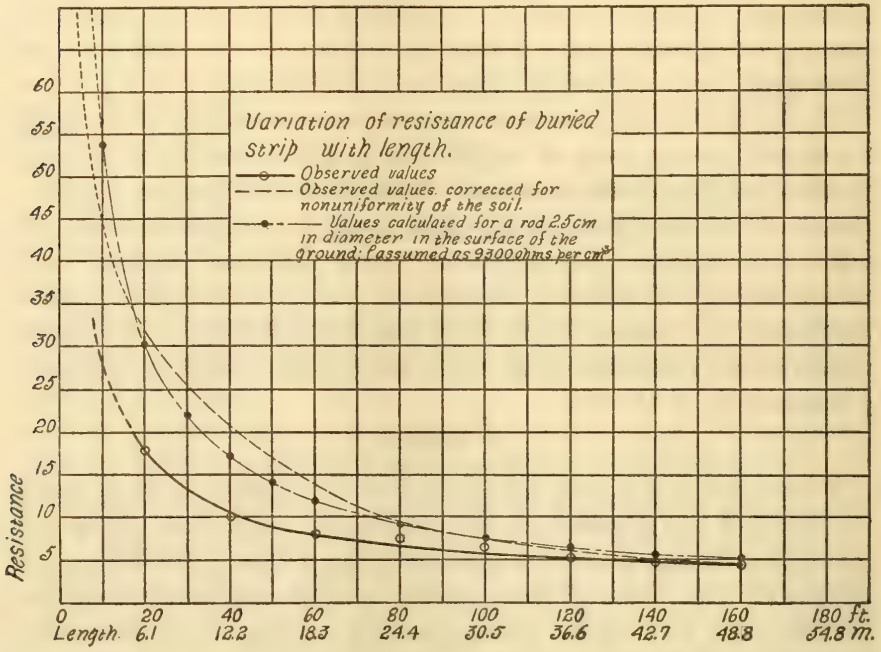

FIG. 17

which it can pick up the earth charge when a lightning stroke occurs. As pointed out heretofore, if conditions exist favorable[4] to a lightning stroke, the charge on the earth covers a considerable area, of which the building may be the center, or at least the point toward which the stroke is likely to be directed. When the stroke occurs, there is a tendency for the charge to rush toward the building, and it is obvious that a network of metal in the ground will collect this moving electricity with greater ease than ground connections at a few points, which in this case would necessarily be of high resistance.

On the other hand, to make a ground connection by means of strips requires a large amount of ground space, and where this

is lacking their use is, of course, impracticable. In addition considerable excavation is required. Nevertheless, there are many places where their use is practicable and it is possible to get an effective connection to earth with them that could not otherwise be obtained.

(*a*) VARIATION OF RESISTANCE WITH LENGTH.—In order to determine the effect of length on the resistance of a ground connection made of strips of metal, 8 specimens of galvanized strap iron 1.5 inches wide and 20 feet in length were buried in a trench 12 inches deep and 160 feet long. Each specimen had leads soldered to its ends, which were brought out of the ground so the resistance of the separate specimens, or any number of them connected, could be measured. To make certain that the ends of the specimens were fully separated from each other, a wooden stake 4 inches wide was driven between them. The resistances to flow of current away from these specimens were measured each month, and a set made on July 27, 1915, when the resistances were somewhat above their minimum value for the year, are given in Table 8. This set of measurements contains values for each specimen and for combinations of the different specimens connected to give lengths from 20 to 160 feet. The results obtained on the different lengths are shown plotted in Fig. 17.

TABLE 8.—Resistance of Buried Strips

Strips	Resistance	Strips in parallel	Length	Resistance	Resistance corrected for nonhomogeneity of soil	Length of rod (Diam 2.5 cm)	*C* for rod	Calculate resistance, assuming ρ= 9300 ohms per cm ^{3}
						Cm		
	Ohms		Feet	Ohms		305	27.7	53.4
3	17.7	3	20	17.7	31.6	609	49.2	30.1
						914	69.3	21.4
4	13.6	3–4	40	10.1	20.5	1220	88.6	16.7
						1524	107.4	13.8
5	25.5	3–5	60	8.2	13.6	1829	125.7	11.8
6	48.2	3–6	80	7.5	9.0	2438	161.0	9.2
7	39.8	3–7	100	6.5	7.1	3050	195.3	7.6
8	21.2	3–8	120	5.2	5.9	3660	229.5	6.5
9	39.5	3–9	140	4.8	5.1	4270	262.5	5.6
10	47.6	3–10	160	4.4	4.4	4880	295.0	5.1
Av.	31.6							

It will be noted in Table 8 that the resistances of Nos. 3 and 4 are much lower than the average for all of the specimens, which is 31.6 ohms. The effect of these low values for the resistances of Nos. 3 and 4 is to depress the left-hand end of the curve of observed values in Fig. 17 and make the right-hand portion flatter than it should be. This arises from the nonuniformity of the soil, whereas if the soil were uniform, the resistance of No. 3 would be 31.6 ohms instead of 17.7, and that of Nos. 3 and 4 connected would be more than 10.1 ohms, the value shown by the table. To give an idea of the slope the curve would have if the soil were uniform, it is necessary to correct the observed values of resistance by means of the formula $R = \frac{R_{av}}{R_1} R'$, where R' is the observed value, R_{av} the average of all the individual specimens, in this case 31.6 ohms, and R_1 the average of the resistances of the individual specimens used in obtaining R'. This is the same as multiplying the observed values by $\frac{\rho_{av}}{\rho_1}$, where ρ_{av} is the resistivity of the soil corresponding to the measured resistance to flow of current away from all of the specimens connected and ρ_1 the resistivity corresponding to R' or the measured resistance to flow of current away from any number of them connected. The values obtained in this manner are also plotted in Fig. 17.

Furthermore, for the purpose of comparison, there is also plotted in Fig. 17, a curve obtained by calculating values of resistance for a rod 1 inch (2.5 cm) in diameter embedded in the surface of the ground to a depth equal to its radius. These values of resistance were calculated from $R = \frac{\rho}{2\pi C}$, C being obtained for the different lengths of rod from the formula $C = \frac{L}{2 \log_e \frac{2L}{d}}$, where L is the length of the rod and d its diameter. The quantity ρ was arbitrarily assumed to be 9300 ohms per cubic centimeter to make the curves for calculated and corrected values nearly coincide.

It appears from these curves that if the length of a buried strip is doubled, the resistance to flow of current away from it is practically halved. In particular, in the case of the rod, when the length is doubled, the calculated resistance is decreased about 45 per cent. In the case of the buried strip, when the length is

increased from 20 to 40 feet the corrected values show that the resistance is decreased about 35 per cent; from 40 to 80 feet, 56 per cent; and from 80 to 160 feet, 51 per cent. When the length of the rod is increased from 20 to 160 feet the calculated resistance is decreased 83 per cent, while in the case of the strip the decrease is 86 per cent. The observed values do not check with these so far as decrease of resistance with increasing length is concerned, for the reason that the trench in which the specimens were buried extended from a region where the resistivity of the soil was of one value to another where it was nearly twice as great, as shown by the resistances of Nos. 3 and 10 in Table 8.

All of the values of resistance mentioned above were obtained on strips lying in a straight line. It is obvious that in this position, if the resistivity of the soil is uniform, the resistance to flow of current into the earth is less than in any other because the value of C is greatest. If the strip were curved or coiled, the resistance would be greater because C would be less. In burying strips, therefore, it is well to remember that for a given length of strip the wider the distribution the more effective the ground connection that will be obtained, unless the resistivity of the soil is nonuniform, and then it is best, in some cases, to put the metal where the resistivity is least. In most places local conditions as to resistivity of the soil will be a large factor in determining the way in which a ground connection is to be made.

(*b*) Variation of Resistance With Depth.—Where buried strips are used, it is not likely that the depth at which they are placed can be arbitrarily chosen, because, in general, the depth that can be attained will be determined by the obstruction which prevents the use of driven pipes. Nevertheless, in some instances it may be well to know something of the effect of depth. This case is similar to the one previously considered of resistance to flow of current away from two driven pipes in parallel. In fact, if a pipe of the same size as the driven pipes were substituted for the strip, the two cases would be exactly the same, for in the case of the driven pipes the electrostatic capacity C applies to the combination of the pipes and their images above the surface of the ground, while in the case of the buried pipe the value of C is the same if the depth is one-half the distance between the driven pipes and the length is the sum of that of one of the driven pipes and its image. The fact that in the case of the driven pipes the surface of the ground cuts the axes of the pipes perpendicularly

and midway between their ends, whereas in the case of the buried pipe the surface of the earth passes parallel to the axis of the pipe and midway between the pipe and its image, does not make a difference in resistance if the resistivity of the soil is the same in the two cases. It follows, therefore, that the resistance to flow of current away from a pipe 20 feet in length buried 3 feet in the ground will be the same as from two driven pipes 10 feet in length and 6 feet apart. Moreover, the curve showing decrease of resistance with increase of depth in the case of the buried pipe will be of exactly the same value and shape as the curve showing decrease of resistance with increase of distance in the case of the driven pipes. For the strip the shape of the curve would not be much different, except, perhaps, when very near the surface of the ground. At a depth of a few centimeters the curves would be practically of the same shape. In burying strips, therefore, it would not be expected that after a depth of 3 feet had been reached there would be a further marked decrease of resistance with increasing depth, because for driven pipes 10 feet in length the rate of decrease of resistance with increasing distance apart becomes very slow after 6 feet is reached. For strips of great length this depth would probably be somewhat increased, but not appreciably under lengths of 40 or 50 feet.

The foregoing deduction is borne out, to a certain degree at least, by data obtained on strips buried at different depths. These specimens were 20 feet long and 1.5 inches wide. One of them buried 6 inches deep showed a resistance of 43 ohms; eight of them 12 inches deep showed an average resistance of 31.6 ohms, as indicated in Table 8; one at 18 inches, 26 ohms; one at 2 feet, 13 ohms; and one at 3 feet, 17 ohms. It appears from these values that after a depth of 2 or 3 feet has been reached, there is no further marked decrease of resistance with increasing depth, but because of the nonhomogeneity of the soil these values must be taken only as an indication of the relationship mentioned above and not as a check upon it. The depth of 3 feet referred to above, means of course, in conducting soil. If there is a stratum of dry earth on top it may, in some instances, be necessary to place strips at a greater depth than 3 feet. To go more than 3 feet in conducting soil, however, will not result in material benefit.

4. PATENTED GROUNDING DEVICES

Many patented devices for making ground connections have been put on the market by manufacturers. Some of these devices have come to the attention of the Bureau of Standards, and in all that have been tested the feature which is supposed especially to recommend them to the prospective purchaser is that they are intended to absorb water in wet seasons and give it out in dry seasons in sufficient quantities to keep the adjacent soil moist at all times and thus prevent marked fluctuations of resistance. A grounding device with this feature incorporated would be very desirable, but practically it is not accomplished by any of the designs that have been tested up to this time. For their absorptive power some of the devices depend upon charcoal and others upon substances the compositions of which are not disclosed by their makers. One consists of a perforated sheet copper cone about 2 feet in height and 6 inches in diameter at the base, which is filled with finely divided charcoal. As regards gases the absorptive power of charcoal is enormous, a given volume of charcoal being able to absorb many times its volume of gas, but as regards water its absorptive power is only of the same magnitude as that of an equal volume of earth. The quantity of water which could be stored in such a small volume of charcoal is therefore not sufficient to be of any moment, and moreover, the charcoal would tend to dry out as fast as the surrounding earth and not lag appreciably behind it. Hence the cone might as well be unperforated and as well be empty as filled with charcoal. The same thing is true of the other devices. As shown later, however, the addition to the soil surrounding an electrode of a soluble salt which is highly conducting in solution materially decreases the resistance in comparison with what it would be with normal earth, and insofar as the substances used in these earthing devices contribute to this effect they are of benefit; but as far as absorbing water in wet seasons and giving it out in dry seasons is concerned their effects are negligible.

As stated above, a number of these devices have been tested. Table 9 contains a summary of the results obtained and also some data which enable comparisons to be made between these special devices and driven pipes and plates. In column 5 are given the resistances of the different kinds of specimens measured August 31, 1915, when they showed the minimum recorded resistance for the year, and in column 6 are given the resistances

of the same specimens measured on December 1, 1915. Where there was more than one specimen of the same kind or size the average value is given. Because of lack of rain and decrease of temperature, the values obtained in December 1 show considerable increases over those for August 31. Column 7 gives the percentage increase of resistance.

It will be noted that none of the special devices showed a resistance markedly lower than the pipes and, in fact, in all but one case the resistance was higher. None of them showed lower resistance than the plates. The figures showing percentage increase of resistance are the most important because the special virtue of these devices is supposed to lie in the comparatively uniform resistance which they maintain. It is shown that the resistance of all the devices increased much more than that of the pipes, and in most cases more than that of the plates. It does not appear, therefore, that the use of these devices will give a result that can not be obtained with pipes, and, moreover, with pipes the cost is less.

TABLE 9.—Comparison of Patented Devices With Pipes and Plates

Specimens	Description	Length or size	Depth	Average resistance, Aug. 31, 1915	Average resistance, Dec. 1, 1915	Percentage increase
			Feet	Ohms	Ohms	
25–26	Paragon ground cones in coke	2 feet	5	39.5	62.2	54.9
27–28	do	1 foot	5	46.4	72.1	55.4
29–30–31	Maxum ground boxes in clay		5	33.2	57.4	72.9
43	L. S. Brach hydroground in clay	Large	5	39.8	61.2	53.8
44–45–46	do	Standard	5	42.2	57.1	35.3
47	do	Medium	5	37.5	52.7	40.5
48–49	Lord Manufacturing Co. disk type hydroground in clay		5	76.1	124.0	63.0
54–55	Federal Sign System cartridge ground plate in clay.	22 inch	5	42.6	71.9	68.8
56–57	do	10 inch	5	47.3	80.6	70.4
32–33 and 36	Plates on edge in clay	2 by 4 feet	6	20.3	29.9	47.3
34–35	Plates flat in clay	do	5	25.4	35.6	40.2
74 and 98 to 104	Three-fourths inch galvanized-iron pipes.	10 feet	10	35.6	47.1	32.3

5. WATER PIPES

As a means of grounding electrical systems water pipes easily come first in point of desirability. In the first place, on account of their great extent they offer but little resistance to flow of current away from them into the earth, the total resistance of

water-pipe ground connections being found in most cases to be but a fraction of an ohm. A resistance of 2 ohms would be extraordinarily high. In the second place, they are easily accessible at service pipes or at other places; and in the third place, ground connections to them are economical in first cost, are easy to inspect, and are permanent. Moreover, the areas covered by electric lighting systems are approximately the same as those covered by water systems, within city limits at least, so it is practicable to ground to them in nearly all cases where ground connections are required. To use the water pipes is, therefore, highly advantageous in many cases, and is especially so where low-voltage alternating-current circuits must be grounded through a low resistance for the sake of personal safety. In this connection it should be emphasized that because of the high degree of security obtained from electrical dangers, the chief advantage is to the public, and in view of this fact, no obstacle should be placed in the way of grounding to water pipes. At the same time, however, it must be shown that the use of water pipes for making ground connections is not in any appreciable degree a disadvantage to the pipe-owning utility. In the past it has been stated that trouble for the utility would arise from three sources, viz, (1) electrolysis by stray currents from grounded circuits; (2) danger to employees while working on service or other pipes to which circuits were grounded; (3) complications from allowing a second public-service utility the use of the pipes. The factors which affect the resistance and effectiveness of water-pipe ground connections and the extent of the possibilities that the use of water pipes for grounding may inconvenience the water utility are discussed under the following heads: (*a*) Resistance of water-pipe ground connections; (*b*) electrolysis by alternating current; (*c*) electrolysis by direct current; (*d*) heating of pipes by current flow; and (*e*) extent of danger to employees of the water utility.

(*a*) Resistance of Water-Pipe Ground Connections.—As stated above, the resistances of water-pipe ground connections are found in most cases to be a fraction of an ohm. Where these low resistances exist, however, it will be found that the pipe joints for a considerable distance from the point of connection give as good metallic contact as will be the case with lead or screw joints, which under favorable circumstances have resistances of only a few thousandths of an ohm. On the other hand, where high resistances exist they will almost always be accompanied by

high-resistance joints such as those made with cement or "leadite," which may have resistances of several ohms or even several hundred ohms. The extent to which the effect of the resistance of the pipe may exceed the effect of the resistance of the soil in hindering flow of current through a water-pipe ground connection is indicated by reference to the case of the buried strip previously considered. It was there shown that if the length of a rod or strip buried in the ground is doubled, the resistance is practically halved. The measured resistance to flow of current away from a buried strip 160 feet in length was found to be about 5 ohms. Assuming the law of variation of resistance with length, as stated above, to hold and neglecting the resistivity of the metal, it is readily seen that if the length were increased from 160 feet to 20 miles the resistance to flow of current away from the strip would be decreased from 5 ohms to a value of the order of 0.007 ohm. Furthermore, if a water pipe 6 or 12 inches in diameter were substituted for the strip, the resistance would be less than 0.007 ohm. Hence, it appears that for water systems of considerable extent, the portion of the total resistance contributed by the surrounding earth is very small. On the other hand, measurements in many cases have shown that an average value for the total resistance is about 0.25 ohm, indicating that the resistance of the pipe contributes an important part and must be considered. In fact, cases may arise where many joints of high resistance in a pipe may make it undesirable as a means of grounding electrical circuits. An example of such a pipe would be one laid with cement joints, or with other insulating joints at short intervals, such as those mentioned above.

In grounding to pipes, however, a distinction must be made between cases where a low resistance to flow of current from an electrical circuit into the earth is desired and those where the object is to keep an electrical circuit, or a conducting body near an electrical circuit, at the same potential as a near by section of pipe. For, even though a length of pipe may have so many joints of high resistance as to make it useless as a ground connection designed to carry considerable current, it may still have sufficient conductance to carry currents large enough to produce severe shocks at moderate voltages in the event of persons making contact with circuit and pipe simultaneously. To prevent accidents of this kind it may be advisable to ground to pipes in some instances even though the resistance to the earth itself is very high.

Cases where such grounding would be necessary are most likely to arise in buildings.

A point which should be mentioned here is the effect which changes in the resistivity of the soil have on the total resistance of a water-pipe ground connection. In the types of ground connections previously considered, the resistivity of the soil is one of the most important factors. To double the resistivity of the soil where one of these ground connections is made would double the resistance. With water pipes, however, the part of the total resistance contributed by the soil is small, unless the resistivity is extremely high, so considerable changes due to drying or other causes will not seriously change the total resistance. In fact, for water-pipe systems of great extent, the resistivity of the soil might change from a value of say 5000 ohms per cubic centimeter to many times that value without markedly affecting the total resistance. In making ground connections of this type, therefore, little attention need be given to the kind of soil in which the pipe is laid. On the contrary, the most important matter in this case is that of high conductance of the pipe joints, such as would be found with lead or screw joints.

It is of interest to compare the average resistance of water-pipe ground connections with that of other forms. For instance, it has been shown previously in this paper that if pipes 10 feet in length are driven in a row 8 or 10 feet apart, their resistance in parallel is about 15 per cent more than it would be if they were at an infinite distance apart, or is not far from inversely as the number. Assuming a single driven pipe in a certain locality to have a resistance of 15 ohms, which is a rather low value, to obtain a resistance of 0.25 ohm would require 50 or 60 pipes 10 feet in length driven in a row 10 feet apart and electrically connected. To obtain the same resistance with plates would require about the same number, unless they were very large, and in addition, it would be necessary to place them more than 10 feet apart. This is plainly impracticable.

At the same time it must be granted, of course, that it is practicable by the use of driven pipes or buried plates to obtain a ground-connection which is amply effective for some purposes. For example, a ground connection can be made which will serve satisfactorily for low-voltage alternating-current circuits where transformers are small and fed by lines of limited current-carrying capacity, and an appreciable degree of protection may be obtained

in this way for lines of almost any capacity. As the power rating of the lines and transformers increases, the resistance presented by the ground connection must decrease if ample protection is to be afforded. The practicable limit of decrease of resistance with driven pipes or buried plates is soon reached, and for circuits of large capacity it is imperative that some other means be found. The most obvious solution of the problem is to connect to water pipes which, in most cities as mentioned heretofore, cover approximately the same areas as the electrical systems. Other means should be resorted to only when the water pipes are out of reach.[24] In the case of lightning rods on the other hand, and also of lightning arresters, machine frames, and any other cases where low resistance is not so essential, driven pipes or plates may serve very well, but there is no case in which water pipes having low-resistance joints can not be used to advantage.

(*b*) ELECTROLYSIS BY ALTERNATING CURRENT.—Such electrolytic damage from alternating currents as may accrue because of earthing electrical circuits to water pipes will, as a rule, be due to currents set up in the pipes by the circuits themselves. It is possible, of course, that there may, in some cases, be stray currents on the pipes from alternating current railways, and grounding electrical circuits to the pipes at several points may divert part of the flow of these currents, as indicated in the next section in regard to direct currents. But these cases are few, and as shown below the extent of the electrolytic damage negligible, so the consideration here given is confined to stray currents set up in the pipes by the grounded circuits, either under normal operating conditions or under conditions of faulty insulation. Referring to Fig. 18, *A* represents an extensive low-voltage alternating-current circuit which is grounded at a number of points to service pipes, these service pipes being all connected to the same water main. It is readily apparent that under normal conditions of operation, or with insulation everywhere in good condition, some current would flow in the pipes, for with an even slightly unbalanced load on the system, current would flow in the middle wire, and because of the accompanying differences of potential between the points *e*, *f*, and *g*, the pipes would carry part of the current, the total current being shared in inverse proportion to the resistances. The current in the middle wire, however, is usually only a small part of the full-load current, and for that reason the current flow in the pipes is not likely to reach serious proportions.

[24] See rule 94, Appendix II.

On the other hand, normally there can be no interchange of current between circuits *A* and *B*. In order for this to occur, the flow would have to take place from *A* through earth wires *a*, *b*, and *c* in parallel, over the water pipe to wire *a* and circuit *b*, and back to *A* on the high-voltage line. Two layers of transformer insulation prevent this, so such an interchange of currents is practically impossible, unless faults develop in the insulation of both transformers. If this should be the case, fuses 1, 2, 3, or 4 would be likely to blow and isolate the low-voltage circuit, or, if they did not blow, the current would be limited to their rated capacity.

With a low-voltage circuit connected to the pipes at a single point as in *B*, Fig. 18, there is obviously no opportunity for any

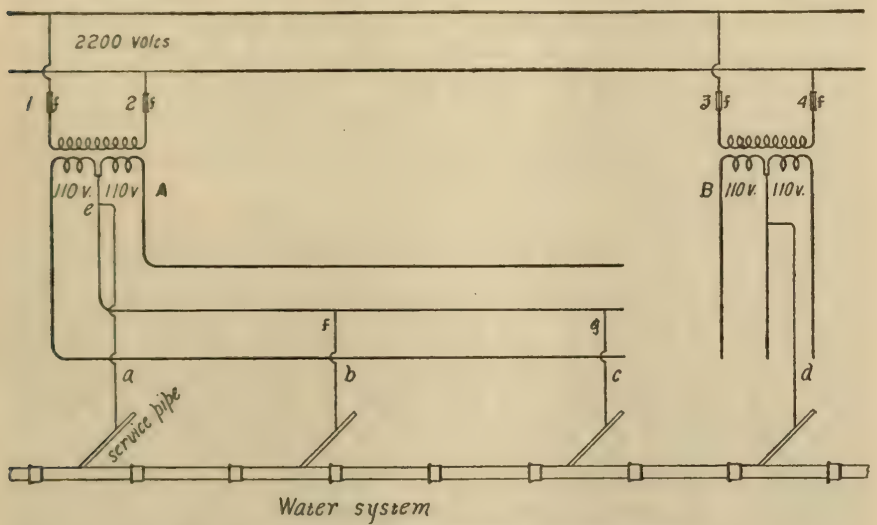

FIG. 18.—*Parallel ground connections to water system*

but the very slightest flow of current into the pipes over wire *d* as long as the insulation remains intact. The slight current that would flow would be due to electrostatic capacity and leakage effects and would hardly be measurable by any ordinary means.

With a condition existing such as that shown in Fig. 4, however—i. e., a contact between wires—considerable current might flow. If the leak should occur to circuit *A*, Fig. 18, for example, the current would pass from one side of the high-voltage line through the fault to circuit *A* and to the pipes over ground wires *a*, *b*, and *c*, whence it would flow through the earth back to whatever accidental grounds there happened to be on the opposite side. This current flow would obviously continue until the circuit was opened either by automatic cut-outs or by switches.

Nevertheless, granting that under normal conditions of operation slight alternating currents may flow continually and that in the event of failure of insulation large currents may flow temporarily, it has repeatedly been shown by experiments both by the Bureau of Standards and by others that the damage which may result by electrolysis from such currents is practically negligible.[25] These experiments, made on both iron and lead, show that with alternating current at commercial frequencies the amount of metal dissolved is but a fraction of 1 per cent of that dissolved by direct current, the quantities of electricity passed being the same. To express the same thing in different words, it may be said that with currents in pipes which are equal in point of quantity of electricity passed, it will take the alternating current hundreds of years to accomplish the damage that would be accomplished by the direct current in a single year. Therefore, from the stray alternating currents which may be found in pipes from grounding low-voltage alternating-current circuits to them no perceptible damage through electrolysis need be feared.

(*c*) Electrolysis by Direct Current.—Electrolysis by direct current may arise where the middle wire of a low-voltage direct-current system is grounded to a pipe at a number of points. The pipe forms a conductor in parallel with the middle wire, and when current flows in the wire current may also flow in the pipe. If the resistance of the pipe is comparable in magnitude with that of the middle wire these currents will also be comparable, being shared in inverse proportion to the resistances. Practically the same effect will be produced where a direct-current system is grounded to a water system at the central station and at other places to driven pipes or plates. The combined resistance of all these pipe and plate grounds in parallel may be low enough to result in a very considerable current flow in pipes near the station. This current flow may, in some cases, be sufficient to result in time in serious electrolytic damage. Damage may also arise from direct currents where an electrical circuit of any kind is grounded to two metallically separate pipe systems, for if there are stray currents from street railways on the pipes, there may be a considerable difference of potential between the two systems, with the result that current flow may be diverted by the grounded circuit and carried into buildings or other places. Another case in which damage may arise from

[25] Technologic Paper No. 72 of the Bureau of Standards.

stray currents from street railways is where an electrical circuit is grounded on each side of an insulating joint installed in a pipe for the purpose of mitigating electrolysis. The grounded circuit here acts as a shunt to the joint and may carry a heavy current if there is a considerable potential difference between the two sections of pipe, thus nullifying in a measure the effect of the joint.

Where direct-current systems alone are concerned, electrolysis from currents originating in the systems themselves, or in street-railway systems and being diverted by grounded circuits from their normal paths, may be obviated by making ground connections only at stations and insulating the rest of the system. No especial advantage is gained by making multiple grounds on direct-current circuits, and by using a single ground any possibility of appreciable damage by electrolysis is prevented. It should be mentioned, however, that while grounds on direct-current systems other than those at the stations are objectionable, an exception may be made in the case of connections to service boxes. These connections are desirable to prevent burning out of lamps and appliances in the event of breakage of the middle wire, and since the resistance to ground of these boxes is generally high, connections to them will not result in appreciable flow of current to earth. In the case of alternating-current systems, however, the use of multiple grounds is, as mentioned later, a decided advantage, and with slight precautions such grounds may be used in nearly all places where their use is required or desirable. The main precaution to be observed is to ground only at points between which there are no appreciable potential differences.

(*d*) Heating of Pipes by Flow of Current.—As shown heretofore, in the event of a failure of insulation in a transformer, or an accidental contact between wires, there may be considerable current flow through the ground connection, and where water-pipe grounds are used, this current may have to traverse a greater or less length of service pipe before it passes into the earth. This, of course, causes a certain amount of heat to be liberated in the pipe, and it has been stated by some that it may be sufficient to raise the temperature of the water high enough to injure the hard rubber parts of water meters. Cases of injury to the hard rubber parts of water meters have been reported, but upon investigation most of them have been found to be due to backing up of hot water from water boilers into service pipes on account of overheating.

Only one case has come to the notice of the Bureau in which there was sufficient current flow in a service pipe to heat the water to a dangerous temperature. In this a street-railway track was bonded to a service pipe which was required to carry a large part of the return current from the cars. A case of this kind, however, is exceptional, and no case has come to the notice of the Bureau in which sufficient current flow to cause heating has occurred from secondary circuits. Moreover, the likelihood of such heating occurring is small, because where there is a possibility of large currents flowing, it will, in most instances, be found that grounding is done either to a large service pipe or to several service pipes in

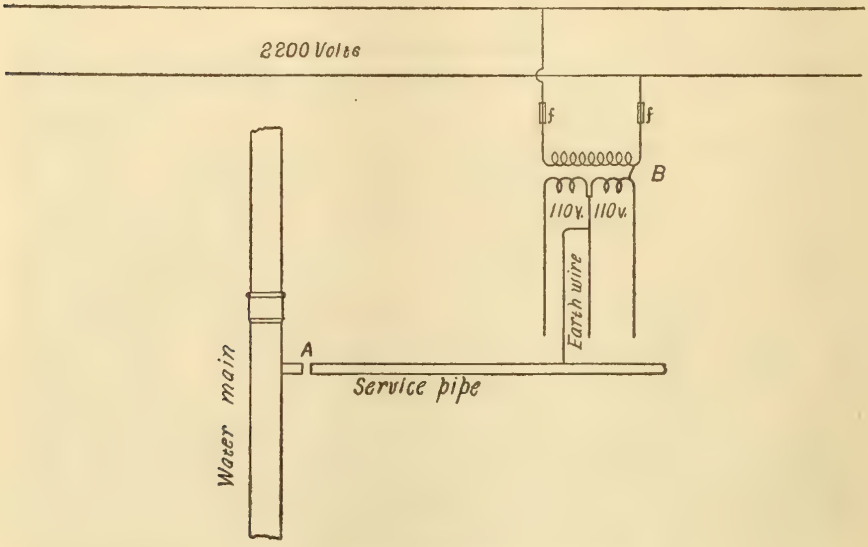

FIG. 19.—*Effect of disconnected service pipe*

parallel, in which case each service pipe carries only a part of the total current.

(*e*) EXTENT OF DANGER TO EMPLOYEES OF THE WATER UTILITY.—In general it may be stated that danger to employees of the water utility is likely to arise only under the conditions illustrated in Fig. 19. This shows a low-voltage circuit grounded at one point to a service pipe, a failure of transformer insulation having occurred at *B*. If the service pipe is disconnected at *A*, the person making the disconnection is liable to an electric shock. The severity of the shock depends upon a number of factors which have previously been discussed, and it has been shown that conditions may easily arise under which the severity would be great enough to cause death. Therefore, with low-voltage circuits

grounded at a single point to service pipes, precautions are advisable to prevent such accidents to employees of the water utility when working on them. This can readily be provided for by requiring the electric company to disconnect ground wires from service pipes when work is to be done on them and reconnect when the work is finished. This is a reasonable and sufficient requirement and has been in force in several places for years with satisfaction to both parties.

In this connection, however, it should be mentioned that the probability of employees of the water utility being injured in the manner described above is exceedingly remote. The foregoing paragraph is intended to indicate only what might occur, for, where water-pipe grounds are used, it will be found that but few low-voltage circuits are grounded at a single point; and where this occurs, the low percentage of failures of insulation, and the infrequency with which service pipes are disturbed, makes the chance of work on a service pipe and a failure of insulation occurring at the same time, almost negligible. Nevertheless, where low-voltage circuits are grounded to service pipes at a single point, the precaution of disconnecting the ground wire before beginning work on the pipe should not be neglected. On the other hand, with multiple ground connections to water pipes, as shown in Fig. 18, precautions of this kind are not necessary. Unless all of the service pipes to which ground wires have been attached are disconnected there is no danger. A person may work on one of the service pipes in perfect safety as far as electric shock is concerned if the connection to the others are undisturbed.

6. MULTIPLE GROUND CONNECTIONS

As previously indicated, it is, in many cases, desirable to ground electrical circuits at more than one point. Moreover, the general practice at the present time is to use multiple grounds, especially where connections are made to water pipes. Where driven pipes, plates, and other small electrodes are used this practice is not so general, but systems in which the custom is followed of making but a single connection to ground on each circuit are not frequently found, unless it be in the case of direct-current systems. The advantages and disadvantages of using multiple ground connections in direct-current and alternating-current systems, the precautions to be observed in their use, and the desirability in some cases of using a common ground wire are set forth below.

(*a*) DIRECT-CURRENT SYSTEMS.—From considerations given in the foregoing discussion on electrolysis by direct current, it is evident that the use of multiple ground connections on direct-current systems is to be avoided to as great an extent as possible, principally on account of electrolysis effects which may arise from the diversion into metallic structures of currents from the circuits themselves. And because the currents carried by many direct-current systems are heavy, these effects may be marked, not only where water pipes are used exclusively, but also where driven pipes and plates are used, particularly if the ground connection at the power house is made to a water system and the rest to pipes and plates. A further reason why multiple grounds on direct-current systems should be avoided, especially multiple grounds to water pipes, is that return currents from electric railways may be diverted from their normal paths of flow by the grounded circuit. In direct-current systems the opportunities for this are greater than in any other because direct-current systems are used mostly in the business districts of cities where traffic is more or less congested and the density of the return current from street cars correspondingly high.

On the other hand, the advantages in the use of multiple grounds on direct-current systems are not great. In fact, in most systems very little is to be gained by making more than a single ground of low resistance at the power house or substation. In the first place, these systems being mostly underground and seldom so situated as to be liable to contact with high-voltage lines, the chance of an abnormal rise of potential against earth, even though the circuit were insulated throughout, is so small as to be of no moment whatever. Consequently, breakage of the ground wire and complete insulation from ground of the entire system, which multiple grounds are designed particularly to overcome, is not likely to prove as serious as in the case of circuits in which dangerously high voltages to ground may appear. In the second place, on account of the large size of the conductors, especially in main lines, and also because of the fact that where they are undergound they are unlikely to be subject to mechanical injury, there is very little chance of a break occurring in the middle wire. Hence, there is no need for multiple grounds to prevent the isolation of a section of line having an unbalanced load with no ground connection. As mentioned heretofore, however, connections to service boxes for this purpose need not

be abandoned, because the resistance of these boxes to ground will, in general, be high. In the third place, to have a single ground connection of low resistance facilitates the detection of accidental grounds. In direct-current systems, therefore, a single ground connection at the central station or substation not only eliminates the possibility of damage by electrolysis but serves every purpose for which grounds on direct-current systems are needed; that is, if the circuits are not exposed to contact with high-voltage lines. Where the latter is the case multiple grounds are preferable. In low-voltage alternating-current circuits, for instance, the desirability of multiple grounds for the purpose of reducing the life hazard is great enough far to outweigh any considerations which may arise in regard to electrolysis.

(*b*) Alternating-Current Systems.—In grounding low-voltage alternating-current circuits the use of multiple ground connections presents the following advantages: In the first place, if a circuit is connected to earth at more than one point, the protection against high voltage is not so likely to be destroyed by breakage of the ground wires as where there is but a single ground connection. In the second place, where multiple grounds are made to water pipes a high degree of safety is afforded employees of the water utility when working on the pipes. In the third place, the greater the number of connections to earth, the less the possibility of a dangerous rise of potential between circuit and ground in the event of a failure of insulation or an accidental contact between wires. This is particularly the case where driven pipes, plates, or grounds other than water pipes are used, since the total combined resistsnce of such grounds in parallel varies approximately inversely as the number. Moreover, in the event of heavy current flow to earth, overheating of the ground wires is not likely to occur because the total current is divided among a number of them. Finally, as shown already, damage from currents in water pipes set up by the circuits themselves is extremely unlikely to occur, and as will be shown, damage by diversion of stray currents from their normal paths of flow is easily avoided. Multiple grounding of low-voltage alternating-current circuits, whether to water pipes or other forms of grounds, is therefore strongly to be recommended.[26]

As just mentioned, however, cases sometimes arise in which it is necessary to guard against trouble from stray currents from street

[26] See rule 92*b*, Appendix II.

railways. Such cases are rare, of course, but they present a possibility which must be taken into consideration. For instance, if a low-voltage circuit is grounded at different points to two metallically separate pipe systems which are at a difference of potential with respect to each other due to stray currents, current will flow from one pipe system to the other over the grounded circuit. The magnitude of this current flow may be sufficient to overheat the wires, or it may be carried by the circuit into the frames of buildings, conduit, or cable sheaths and cause damage by electrolysis. A similar effect may be produced if a circuit is grounded at one point to a water pipe or street car rail which is at a potential difference of several volts from ground and at another to the steelwork of a building or some other metallic structure. The metallic structure takes the potential against ground of the pipe or rail, and danger of electrolysis ensues.[27]

Another way in which stray currents may be diverted from their normal paths of flow is by grounding a low-voltage circuit on each side of an insulating joint which has been installed in a water pipe for the purpose of mitigating electrolysis. The circuit then acts as a shunt to the joint, and the resulting current-flow over the wires may not only cause overheating or electrolysis but also in a measure nullify the effect of the joint. To avoid trouble, both on account of electrolysis and interference with the operation of the circuit, this general rule should be followed. In every case where a low voltage circuit is to be grounded at more than one point, the ground connection should be made at places between which no appreciable differences of potential exist.[28]

A statement should also be made here in regard to grounding the armor or sheathing of extended power or telephone cables to water pipes, for the same precautions must be observed in the case of these sheaths as in the case of low-voltage circuits. In fact, where it is desirable to ground any conducting body of considerable length to water pipes at more than one point, careful consideration should be given to the possibility of picking up enough stray current to cause trouble, either from electrolysis or from overheating. On the other hand, where multiple grounding is done solely by means of driven pipes or plates, the possibility of picking up enough stray current to cause trouble is practically negligible; for in the first place, the potential differences usually found between points in the soil itself do not exceed a very few volts, unless it be between points remote from each other but very

[27] See rule 94*d*, Appendix II.

[28] See rule 94*a*, Appendix II.

near to pipes or rails carrying heavy current flow; and in the second place, the resistances of pipe and plate grounds are so high that at the low voltages encountered but very little current flow over the grounded conductor results. Hence, in making multiple grounds with driven pipes or other electrodes of small extent, little care need be exercised in regard to stray currents, but in the case of water-pipe grounds, as mentioned above, care, in some cases at least, is necessary.

Wherever such care seems to be called for, the resistance of the pipe line between the two farthest removed points of connection can be measured to make certain that no insulating joints are present. If there are no insulating joints, the resistance will, in general, be found to be but a fraction of an ohm. If there are insulating joints, it may be as much as an ohm or even several ohms. In the case of separate pipe systems, voltage measurements between them will generally give the desired information. A better method, perhaps, of finding whether a circuit can be grounded at more than one point is to ground its extreme ends with a recording ammeter in circuit and ascertain whether current flow results. If there is none, or if it does not amount to more than a very few amperes at any time during the day, grounding at more than one point may be considered practicable. If, however, the current flow is sufficient to cause unbalancing of the voltage or overheating of the wires, it will, of course, be necessary to confine the number of ground connections to one or else to several very near each other.

(*c*) Common Ground Wire.—In sections where water pipes are not available and the soil is not particularly favorable toward making grounds with driven pipes or other devices, the problem of securing adequate protection against high voltages is best solved by making use of a common ground wire. The usual form of common ground wire is illustrated in Fig. 20. Here a wire of the same size as the line wires connects a number of low-voltage circuits, with ground connections installed at each transformer and at advantageous points along the line. Thus the protection of each circuit is derived, not only from the grounds on the circuit itself but also from those on the ground wire and all of the other circuits in parallel. If the extent of the ground wire is considerable and it is grounded at many points, the degree of protection afforded, while not equal to that offered by water pipes, may be rated as next to it.

In providing grounds for such an installation as that described above, advantage should be taken of local conditions—that is, rather elaborate ground connections should be made in locations which are the most favorable as regards soil and moisture—and use should also be made of local water systems, driven wells, and other underground metal. If care in this respect is exercised, good results may be obtained even where the soil consists principally of gravel, sand, or stones.

The cost of a common ground wire where a special wire has to be run to bridge gaps between low-voltage circuits is, of course, the same as for a line wire. Aside from this the expense necessarily incurred in excess of that which would otherwise be required is inconsiderable. It is advisable, however, to make as many ground connections as practicable, because the greater the

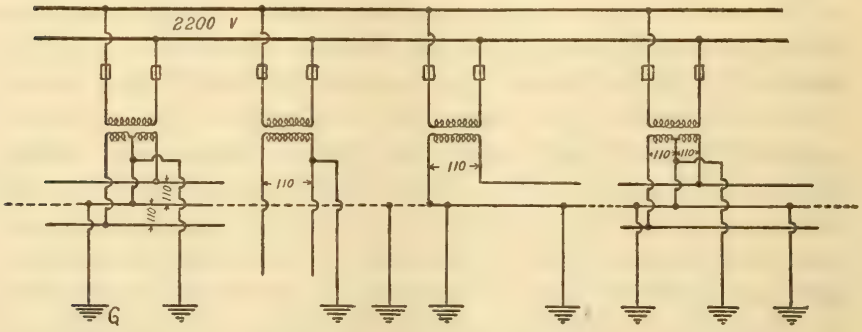

FIG. 20.—*Common ground wire system.*

number the better the protection that is afforded. This is also true whether a common ground wire is used or not. In fact, a single ground connection on a low-voltage secondary circuit should be avoided wherever possible, and multiple grounds used instead whether connection is made to water pipes or to grounds of other forms. The increase in the degree of protection is well worth the expense.

7. VARIATION OF RESISTANCE OF GROUND CONNECTIONS WITH SEASONS

The seasonal variation of resistance of ground connections is great enough in some localities to be of considerable importance. The principal factors which cause this variation are the temperature and moisture content of the soil. For changes in the temperature and moisture content of soil cause its resistivity to change between wide limits, and since the resistance to flow of current away from an electrode buried in the earth depends directly upon

the resistivity of the soil, changes in the latter will also cause changes in the resistance to flow of current. The degree to which such changes will affect the total resistance of an earth connection depends upon the extent of the electrode. With electrodes of limited extent, such as driven pipes, the part of the total resistance contributed by the metal is negligible in comparison with that contributed by the soil. Hence, changes caused by temperature and moisture content cause practically proportional changes in the total resistance. With electrodes of great extent, however, such as water pipes, the case is different. The total resistance of an earth connection made in this way may depend in larger part upon the resistance of the pipe per unit length than upon the resistivity of the soil, so changes in the latter are not likely to produce serious changes in the total resistance. The effects of the temperature and moisture content of soils on their resistivity are discussed briefly below, and some experimental data are also given which show the magnitude of the variation in resistance of ground connections with seasons that may be expected under climatic and soil conditions similar to those prevailing in the vicinity of Washington.

(*a*) TEMPERATURE EFFECTS.—The effect of temperature upon the resistivity of soils has been studied at the Bureau of Standards,[29] and it has been found that at a temperature of 18° C the rate change of resistivity with change of temperature is about 5 per cent per degree. This value holds approximately until 0° is reached. At this point a sudden change in the rate occurs and it becomes more rapid. From −4 to −8° it is about 30 per cent, from −8 to −12° about 13 per cent, and from −16 to −20° about 9 per cent. Reducing the temperature from +20 to −19° increases the resistivity more than 200 times, with a sharp change in the rate of increase at 0°, of course, where the water contained in the soil begins to freeze. With decreasing temperature below 0° the resistivity tends toward values commonly associated with dielectrics. These data were obtained on a sample of clay containing 18.6 per cent of moisture and having a resistivity of 6260 ohms per cubic centimeter at 20°. With different soils, deviations from these figures may be expected but the order of magnitude will remain the same.

It is apparent, therefore, that a ground connection which is intended to be operative at all times of the year must be well

[29] Technologic Paper No. 25, Bureau of Standards, Electrolytic Corrosion of Iron in Soils.

below the frost line. In some localities in the United States where the winter seasons are severe, this may be at a depth of 6 or 8 feet; in others, it may not exceed a few inches, and there are places where the ground does not freeze at all. If at any place freezing temperatures prevail for some time, however, considerable increases in the resistance of ground connections may be anticipated, unless it be in the case of water pipes. These, in general, are laid well below the frost line, and as pointed out above, great changes in the resistivity of the soil are required to produce material changes in the resistance of ground connections made to them. Above freezing, the effect of change in temperature upon the resistivity of soil is not great, and for that reason, the resistance of water-pipe ground connections will be found fairly uniform the year round, at least as far as the effect of temperature is concerned.

(*b*) MOISTURE EFFECTS.—The moisture content of soil is much more important than temperature in its effects on the resistivity at temperatures above freezing. For a particular sample of red clay, it has been found [30] that decreasing the moisture content from 22 per cent to 16 per cent increases the resistivity about 2 times, from 16 per cent to 11 per cent about 20 times, and from 11 per cent to 5 per cent about 10 times. Decreasing the moisture content from 30 per cent to 5 per cent increases the resistivity about 400 times. A decrease from 22 per cent to 5 per cent causes a change in the resistivity from 6800 ohms per cubic centimeter to 2 340 000 ohms per cubic centimeter. When air dried this soil contains about 5 per cent moisture. For different soils the resistivity for a given moisture content may differ widely, but the foregoing figures may be taken as indicating the magnitude of the changes to be expected in the case of any soil as the moisture content varies.

The importance of the effect of moisture is thus made apparent. A difference of a few per cent makes a very marked difference in the effectiveness of ground connections made with electrodes of limited extent, especially at low values; that is, 15 per cent or less. Hence, every effort should be made to select locations for ground connections where the greatest amount of moisture is to be obtained; that is, if there is any choice in the matter. Many cases will arise where waste water of some kind can be utilized to good advantage.

[30] Technologic Paper No. 25, Bureau of Standards, Electrolytic Corrosion of Iron in Soils.

(*c*) EXPERIMENTAL RESULTS.—In order to determine the seasonal variation of resistance of earth connections which might be expected under the climatic and soil conditions prevailing in the vicinity of Washington, measurements were made at intervals of one month for about a year and a half on the specimens already described in this paper. These specimens, it may be repeated, consisted of driven pipes, plates, strips, and a number of patented devices. The ground in which the tests were made is a rather stony clay, which has been found by measurement to be of somewhat higher resistivity than most of the soils met with in other localities, although the soil in some places will be of even higher resistivity and, hence, worse for the purpose of making ground connections. The measurements were made by the ammeter-voltmeter method.

The results of measurements on a number of specimens representative of each type are shown plotted in Figs. 21, 22, and 23. Where more than one specimen of each kind was available, the average resistance is given. As would be expected, the maximum resistance for nearly all of the specimens occurs in midwinter and the minimum in midsummer. The average total change is seen to be about 70 per cent. In particular, for 0.75-inch pipe 3 feet long the maximum is 1.7 times the minimum; for 0.75-inch pipe 10 feet long, 1.4 times; for strips 20 feet long, 1.8 times; for a plate 2 by 8 feet, 1.7 times; for Paragon ground cones, 1.7 times; Maxum ground boxes, 1.6 times; Brach hydrogrounds, 1.6 times; Lord Manufacturing Co. hydrogrounds, 1.9 times; and Federal Sign System cartridge ground plates, 2 times.

With the exception of Nos. 8 and 9, Fig. 23, there seems to be no material increase of resistance with time. In fact, it may be considered that there has been an improvement in the condition of the ground connections, because the resistances of January, 1915, are practically the same as of January, 1916, although on the latter date the soil was drier than on the earlier date, and the temperature about the same. With Nos. 8 and 9, however, the case is different. These specimens show a marked increase of resistance during the course of the year. On the other hand, it is seen that in several cases there was a marked decrease of resistance during the first month after the measurements were begun. This is largely due to the fact that holes were dug and allowed to stand open for several days before the electrodes were buried. When the holes were filled the metal was surrounded

by soil which had been more or less dried by exposure to air so the resistance to flow of current was at first rather high in comparison with values obtained later.

In making the measurements mentioned above, it was necessary to determine each time the resistance of a ground connection made to the city water system. The conductor leading to the water main consisted of 250 feet of enameled steel conduit in series with a long service pipe. The conduit was laid underground with joints which had been screwed together after being daubed with a mixture of red lead and oil. The total resistance of this ground connection was found to be about 1.7 ohms, of which ap-

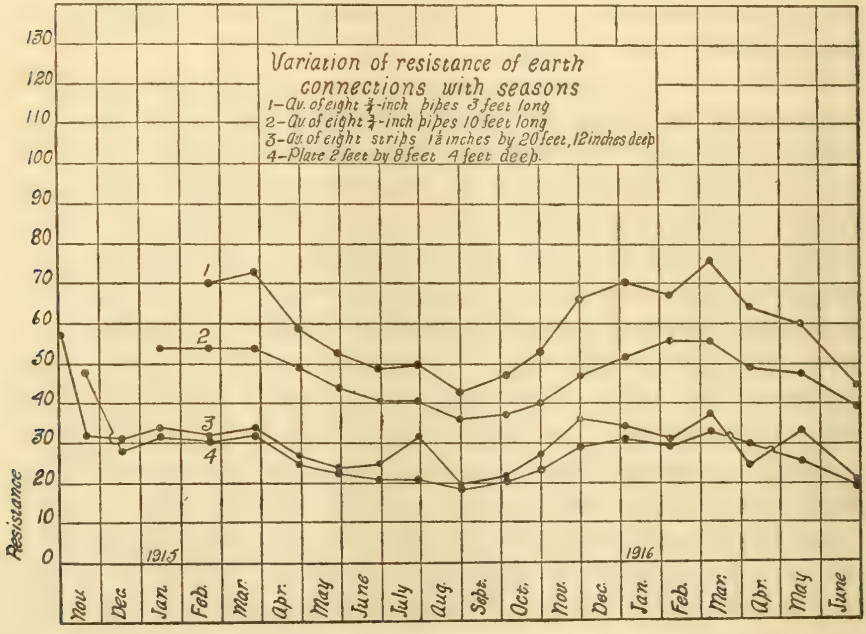

FIG. 21

proximately 1 ohm was found to be in the conduit. The remaining 0.7 ohm was the resistance offered by the service pipe and water main. Measurements each month showed no variation of resistance with time that could not be attributed to errors in measurement.

It should be noted in connection with these tests that there was but little freezing weather and most of the time the soil was fairly moist, and at times, especially in January, 1915, very wet. There were no extremely cold or dry periods. The only dry periods of any consequence occurred just before the measurements made at the end of March and at the end of July in 1915. Preced-

ing the measurements at the end of August there was much hot weather with several heavy rains, 3.32 cm (1.31 inches) of rain falling on August 30. On August 31 the lowest recorded resistance for the year was obtained. Following August the precipitation was light, with the exception of one or two hard rains in October, and the temperature decreasing, so the resistances increased steadily.

Other data showing the seasonal variation of resistance of earth connections have been published by Hayden [31] from tests made on some driven pipes. These pipes were 3.75, 2.75, and 3.1 feet in length, respectively. Measurements were made on them at

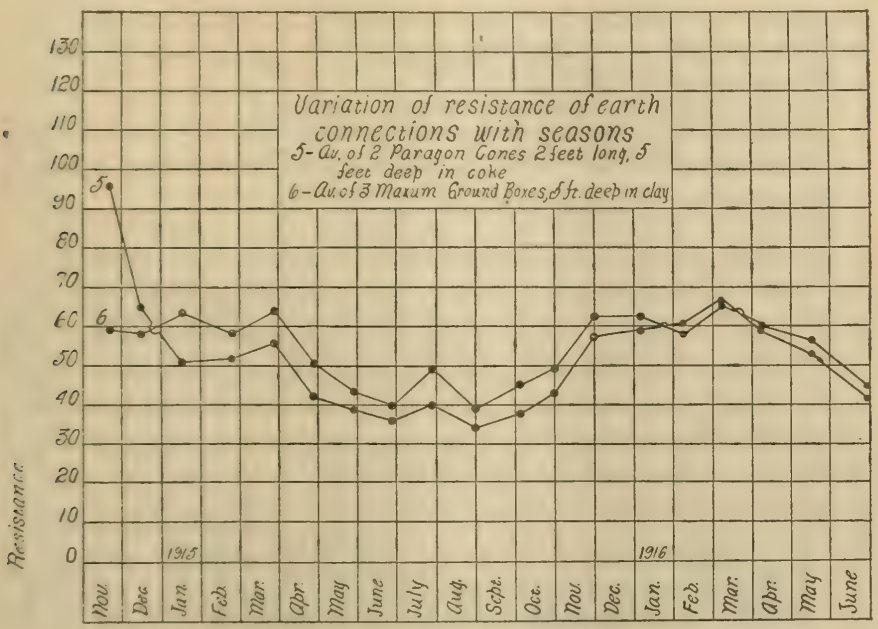

FIG. 22

regular intervals over a period of three years. The curves correspond to those described in the preceding paragraph in so far as the time of maximum and minimum values of resistance are concerned, the maximum value occurring in February and March and the minimum in July and August; but the differences between maximum and minimum values were found to be much greater than in the present investigation. In the case of one specimen, the maximum was three times the minimum, and in another seven times the minimum. This was probably due to deeper frost in the wintertime. Some of the curves given by Hayden are much more in detail than those in Figs. 21, 22, and 23 and

[31] Trans. A. I. E. E., 26, Pt. II, p. 1209.

show the variation from day to day. Curves showing the variation from day to day are of a saw-toothed form, because a heavy rain or a few dry days produce considerable abrupt changes. As shown by Hayden's curves, these in some cases may be as much as 20 per cent in two or three days, but they are not important. It is the large changes from season to season that are of real significance.

It is obvious, of course, that measurements such as those described above can be taken only as indicating the magnitude of the changes that may be expected in the particular locality in which they are made. These changes will be different for different soils

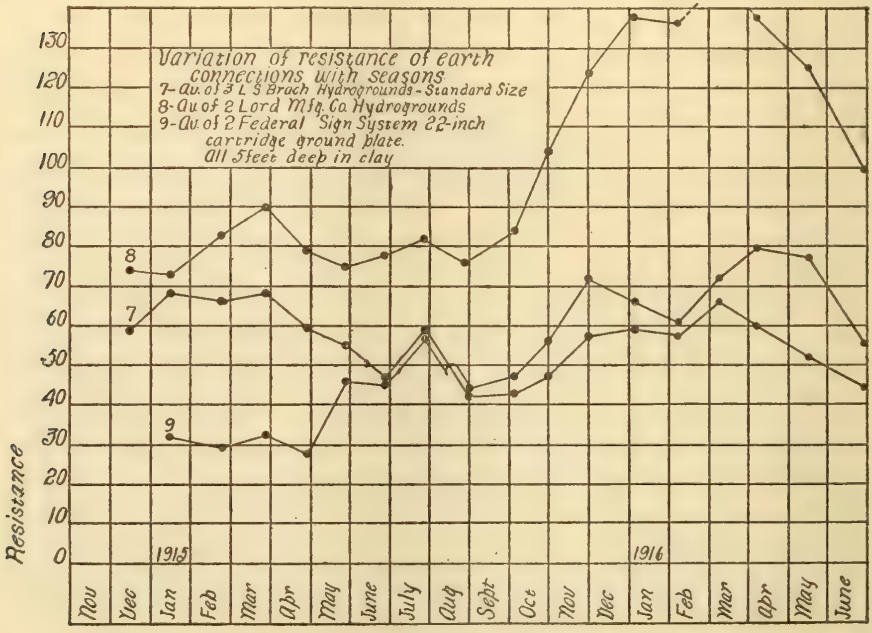

FIG. 23

and for different climatic conditions. They may even vary widely from year to year for the same locality. Thus, a very cold winter followed by a hot summer with heavy rainfall would produce an exceedingly great change in the resistance, whereas a mild winter followed by a dry summer might show nearly uniform resistance throughout the year. Moreover, with a given variation in temperature and rainfall, the soil conditions have great influence; for if the soil is of fine texture with bedrock at a great depth, moisture is accumulated in wet seasons and retained to a greater or less extent in dry seasons, which tends to produce a uniform value of resistance from season to season. On the other hand,

with soil of a loose sandy or gravelly nature, moisture is not retained so readily, and large fluctuations of resistance may be expected. With bedrock near the surface of the ground, large variations of resistance may also be expected whatever the nature of the soil, because evaporation rapidly exhausts the supply of moisture which can be stored in wet seasons in the thin layer covering the rock. Ordinarily the depth at which ground connections are placed—that is, within practical limits—also has some influence on changes in resistance. This, in some cases, may be considerable, and in others it may be negligible. In the measurements described above it will be noted that in the case of driven pipes 3 feet long the maximum was 1.7 times the minimum, while in the case of pipes 10 feet long the maximum was 1.4 times the minimum. Generally the deeper a ground connection is the more uniform its resistance is likely to be. In passing, it should be emphasized again that the foregoing remarks apply more particularly to ground connections made with electrodes of limited extent.

8. INCREASING THE CONDUCTANCE OF GROUND CONNECTIONS

As indicated heretofore in this paper, the normal resistivity of the soil in most localities is such as to make the resistance of a ground connection made with an electrode of limited extent rather high. In such places ground connections of low resistance can be made by placing a sufficient number of electrodes in parallel, but this requires considerable space and is expensive, especially if the resistance required is comparable with that of ground connection made to a water pipe. In order to lessen this difficulty an expedient has been many times resorted to, which is that of reducing the resistivity of the soil immediately surrounding the electrode, thus enabling the attainment of a low resistance with a much smaller number of electrodes than would otherwise be the case. To reduce the resistivity of soil it is only necessary to dissolve in the moisture normally contained in it some substance which is highly conducting in its water solution. There are many substances which could be used for this purpose, but most of them are expensive or are otherwise unsuitable. The substance most often used is salt (NaCl). Another which could be used to greater or less advantage is calcium chloride ($CaCl_2$). Both are highly soluble in water, are highly conducting in solution, and are comparatively cheap. The ratio of the conductivities of solutions of these substances to that of ground water may be stated to be of the order

of 1:100. They possess disadvantages, however, in that they are more or less corrosive, at least toward iron, and their effects are not permanent. The supply of salt must also be renewed at intervals to replace that washed away by water percolating through the soil.

Another method of increasing the conductance of ground connections, especially buried plates, is that of surrounding the electrode with charcoal or coke. It is thought by many that this method presents distinct advantages, but others discredit it. Experiments by Sloss and Fish,[32] for instance, do not show that the addition of charcoal reduces the resistance of a ground connection, and experiments by Ford [33] point to the same conclusion. In both of these investigations it was also found that ground connections made in this way vary in resistance with seasons and increase in resistance with age to a greater extent than ground connections made without these substances. In fact, all of the results obtained seem to indicate that either charcoal or coke is more of a disadvantage than a help. This experience is not reported from other quarters, however, and it may be that the instances cited above are exceptional. At any rate the idea is prevalent in many places that a good ground connection can not be made without using one or the other. Their effects in reducing the resistance of a ground connection have been attributed by some to their power of attracting and absorbing moisture, which is stated to tend to lower the resistance to flow of current away from the electrode into the earth. Whether this is the case is open to question. It seems more likely that a view held by others more nearly represents the facts. This view is that the highly conducting coke or charcoal has an effect equivalent to that produced by increasing the surface area of the electrode in contact with the soil.

In order to determine some of the effects of salt and coke, and more particularly the time required for rain water seeping through soil to wash the salt away, several specimens were buried and measurements of resistance made on them at intervals of one month for about a year and a half. A discussion of the results of these experiments, and also the results of some measurements of the resistivity of samples of soil containing different quantities of salt, is given below.

(*a*) Effects of Salt.—To obtain an idea of the time required to eliminate the effects of salt by percolation of moisture through

[32] Electrical World, 55, p. 1134. [33] Electrical World, 58, p. 622.

soil two specimens were buried, one consisting of a strip of No. 20 gage galvanized sheet iron 1.5 inches wide and 60 feet long, and the other of a plate of No. 16 gage galvanized sheet iron 2 by 8 feet. The strip was buried in a trench 12 inches deep with 1 pound of salt per foot of strip. The plate was buried in a hole 4 feet deep, with 74 pounds of salt. The soil, as before stated, was a rather stony clay of fine texture.

The results of the monthly measurements of resistance have been plotted in Figs. 24 and 25, curves (3) and (6). In both cases results obtained on similar specimens buried in clay without salt are also shown to aid comparison. In the case of the

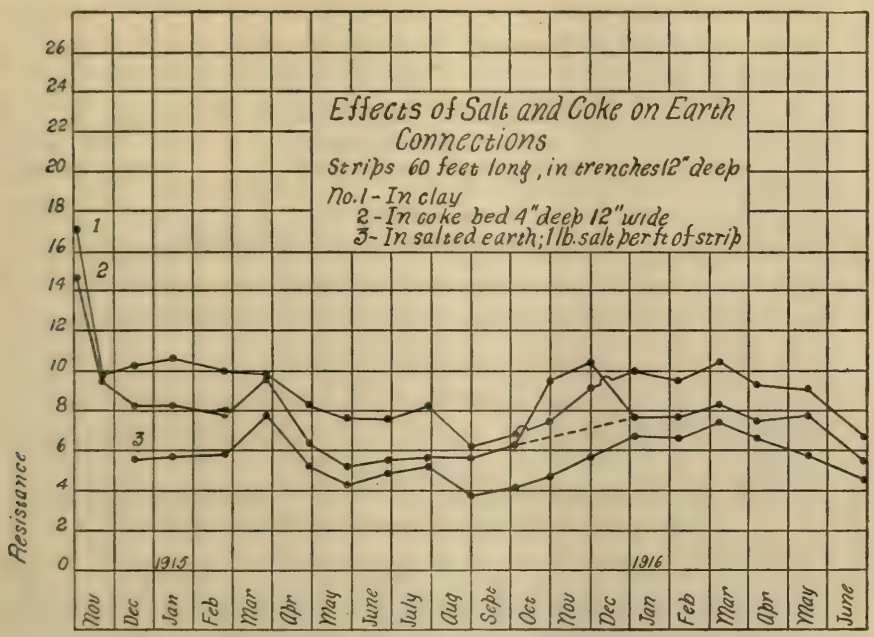

FIG. 24

strip, the addition of the salt appears to have reduced the resistance by about 30 per cent. This is somewhat less than would be expected. There is, however, no way of telling what the resistance would have been if the strip had been buried in the same trench without salt, and it may be that curve (3) under those conditions would be considerably above curve (1). This supposition is strengthened by the fact that measurements made on other specimens indicate the resistivity of the soil in the vicinity of the specimen from which curve (1) was obtained to be lower than elsewhere. The apparent reduction of 30 per cent is therefore undoubtedly to be considered as rather small. On

the other hand, in the case of the plate, the reduction of resistance is about 75 per cent. In addition, the specimens from which curves (4) and (6) were obtained were only about 20 feet apart, and nothing developed in the course of the measurements which would suggest that there was much difference in the resistivity of the soil in the two places. The reduction shown may therefore be taken as indicating the actual change caused by the salt.

The most important fact brought out by these tests is that of the lasting effect of an application of salt, for there appears to be no permanent increase of resistance of either the strip or the plate during the period covered by the measurements. More-

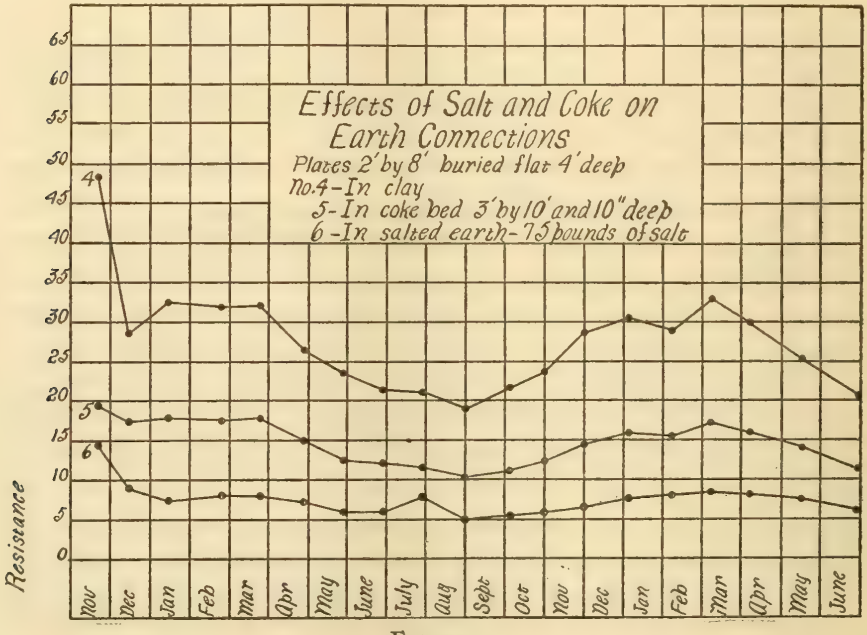

FIG. 25

over, the precipitation during this period was close to normal, the records of the Weather Bureau showing the actual precipitation from November 1, 1914, to January 31, 1916, to be 47.78 inches, and the normal precipitation to be 52.74 inches. The rate of washing away of the salt may therefore be considered as being practically as rapid as during a similar period of normal precipitation. Hence, it is not likely that with soil of the kind in which these ground connections were made, the salt would have to be renewed oftener than once in two years. This soil, however, is of close texture. In soils of loose texture, percolation of moisture from the surface downward would be more rapid during

rainfall, and salt would be carried away at a greater rate; and when once carried to a considerable depth in loose soil the tendency for the solution to return by capillary action during dry seasons would be much less than in soil of close texture. Consequently, the salt would have to be renewed oftener than in soils through which water does not pass so readily, but to state definitely the length of time between renewals in any case would require further experiments.

A question which arises is that of the amount of salt to be used to produce the best results from a ground connection. To obtain some information on this subject, 12 samples of dry red clay were prepared by adding water until the contained moisture amounted to 30 per cent by weight of the dry earth, and salt (NaCl) in different proportions to each sample until the moisture in the different samples formed solutions ranging in strengths from 0 to 16.6 per cent by weight of the water. The salt was dissolved in the water and the resulting solution and earth thoroughly mixed, after which the samples were placed in air-tight glass jars and allowed to stand two days for diffusion of the solution to take place. The resistivity of each sample was then measured by tamping it into a glass-lined cylinder with an iron bottom, forcing an iron piston down upon it, and using alternating current at 60 cycles per second with an ammeter and voltmeter. The results of these measurements are shown plotted in Fig. 26. It is there seen that the addition of 0.33 per cent of salt to the contained moisture causes the resistivity to drop from 4100 ohms per cubic centimeter to about 700 ohms per cubic centimeter. At this point the rate of decrease of resistivity with increase in the percentage of salt in the moisture becomes much slower but is still considerable, and with the moisture containing 16 per cent salt the resistivity is about 55 ohms per cubic centimeter. After 10 per cent is reached, however, further additions of salt produce but slight changes in resistivity, at least as compared with the changes produced by the first small additions.

In making this test a record was kept of the volume and weight of the earth used, the volume being taken as that of the tamped earth when ready for the resistivity measurements. The weight of the dry earth was found to be about 90 pounds per cubic foot. The moisture content of soils ranges from about 15 per cent in dry seasons to 35 or 40 per cent in wet seasons, so the weight of the contained moisture ranges from 13.5 to 36 pounds per cubic

foot. From the curve of Fig. 26 it is seen that if enough salt is dissolved in the moisture to make of it a 0.5 per cent solution, the resistivity of the soil will be reduced to about 14 per cent of its normal value. To produce this result with 40 per cent moisture in the soil would therefore require the addition of about 0.18

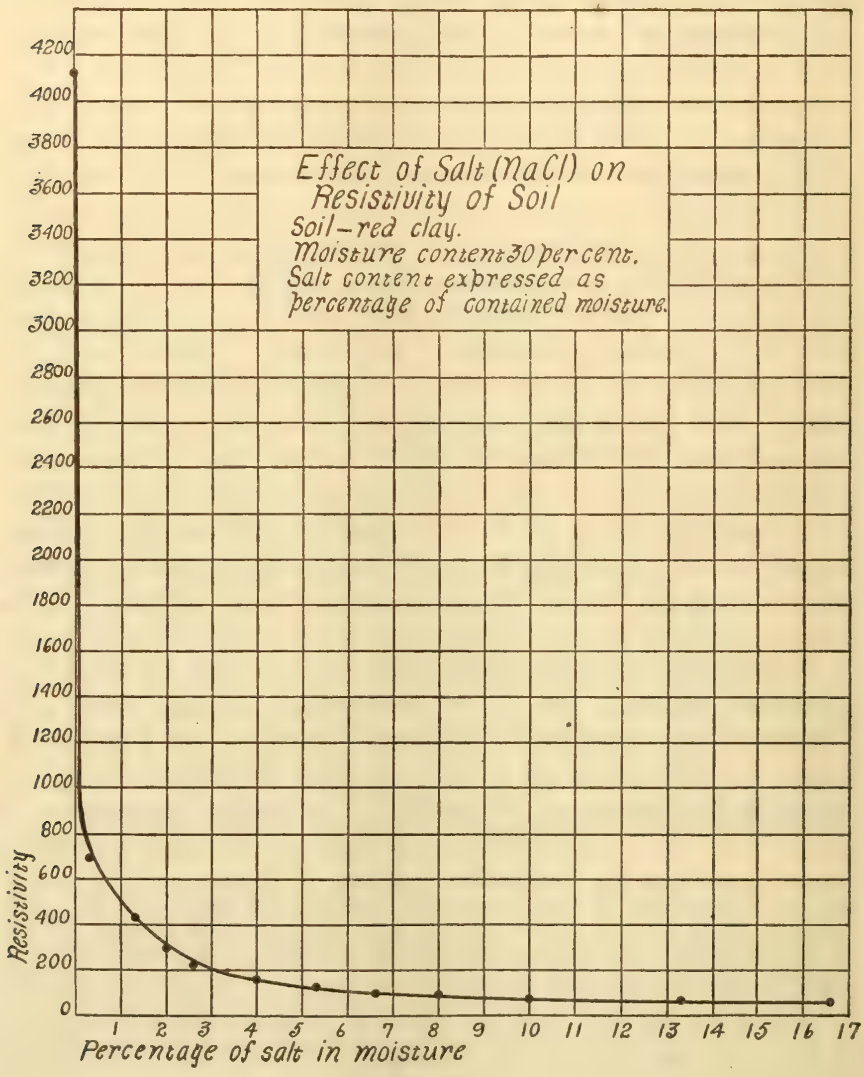

FIG. 26

pound per cubic foot of earth; to reduce the resistivity to 10 per cent of its normal value would require the addition of 3 times as much, to 5 per cent of its normal value 6 times as much, and so on.

From these data may be obtained an idea of the quantity of salt required to produce large reductions in the resistance of

a ground connection. With an electrode of any shape, the production of large changes would necessitate the addition of salt to all of that portion of the surrounding earth which contributes in any considerable measure to the resistance to flow of current. For example, let a pipe driven in soil of fairly uniform resistivity be considered. As will be shown later, if current is flowing away from such a pipe into the earth, approximately 90 per cent of the total difference of potential between the pipe and a point in the earth a great distance away occurs in a region within 6 feet of the pipe. Hence, if to the water contained in a cylinder of earth 12 feet in diameter and extending some distance below the bottom of the pipe enough salt were added to make of it a 0.5 per cent solution, the portion of the total resistance contributed by this cylinder would be reduced to 14 per cent of its normal value. If the total resistance were originally 25 ohms, the resistance after being salted as described above would be about 5.6 ohms, for that part of the soil contributing 10 per cent of the original resistance would be unaffected, while the remainder, or the portion contributing 22.5 ohms, would be so affected that its resistance would be reduced to 3.15 ohms, the sum of the components then being 5.6 ohms. If the pipe were 10 feet in length, the cylinder of earth 12 feet in length and containing 40 per cent of moisture, the weight of salt required would be 245 pounds, since the volume of the cylinder is 1360 cubic feet.

By increasing the quantity of salt a still further reduction of resistance could be effected. If salt were added until the contained moisture become a 10 per cent solution the resistivity of the soil would be about 1.87 per cent of its normal value. The total resistance of the earth connection would then be about 2.9 ohms. This, however, would require 20 times as much salt as in the case described in the preceding paragraph, or about 5900 pounds, and the added reduction would not be worth the added expense. The same result could be accomplished for less than half the cost by driving two pipes 10 feet apart and using but a fraction of this amount of salt. In fact, in any case where a ground connection of a given resistance must be made, especially if the resistance required is very low, maximum economy will probably lie in the use of several electrodes combined with an amount of salt which will not be a source of excessive expense for renewals.

Nevertheless, the foregoing data indicate that a more liberal use of salt than has heretofore been the general practice is desir-

able. In the past it has been considered by many that when a few pounds of salt had been added all had been done that could reasonably be expected. But it is obvious from what has been said above that several hundred pounds could be used to advantage with earth connections that are of importance, and where low resistance is necessary, and for earth connections of almost any kind a hundred pounds would not be too large an amount.

Moreover, with a liberal use of salt an advantage aside from that of reduction of resistance is obtained, although it is much less than has sometimes been stated to be the case. This is in an increased uniformity of resistance; that is, alternate dry and wet or hot and cold seasons make smaller proportional changes in salted ground connections than in those that are unsalted, or are made with charcoal or coke. Referring to Fig. 26, it is apparent that if the moisture around an earth connection contained enough salt to form a 0.5 per cent solution at a moisture content of 40 per cent, a reduction of the moisture to 20 per cent would increase the concentration of salt and hence decrease the resistivity of the solution to an extent sufficient under some conditions largely to counteract the effect of the drying. For instance, measurements of the resistivity of soil containing different percentages of moisture show that changing the moisture from 40 to 20 per cent changes the resistivity by about 30 per cent.[34] Doubling the concentration of salt produces practically the same change in the opposite direction, so the two tendencies would almost exactly counteract each other. With further drying, however, the rate of increase of resistivity with decrease of moisture becomes much more rapid, and, on the other hand, with increasing concentration of salt the decrease of resistivity becomes slower, so the effect of the salt in producing uniformity of resistance become less with increasing dryness of the soil.

With regard to minimizing the effects of changes in temperature salt is probably of most service in lowering the freezing point of the solution, thus putting the point of sudden large increase in the resistivity of soil several degrees below the freezing point of water. The relative importance of the effect of salt in producing uniformity of resistance is apparent on examination of Fig. 25, where it is shown that the ratio of maximum to minimum resistance is about 1.4 for the plate put down with salt and 1.7 for the plate put down without salt.

[34] Technologic Paper No. 25 of the Bureau of Standards, p. 57.

(*b*) Effects of Coke.—In order to obtain some information as to the extent to which coke may be depended upon to reduce the resistance of ground connections two specimens were put down, one of which consisted of a strip of No. 20 gauge galvanized sheet iron 1.5 inches wide and 60 feet long. This strip was buried in a trench 12 inches deep, with a bed of coke filling the trench to a depth of 4 inches and of the same width as the trench which was about 12 inches. The other specimen was a plate of No. 16 gauge galvanized sheet iron 2 feet wide by 8 feet long, which was buried flat in a hole 4 feet deep, with a bed of coke filling the hole to a depth of 10 inches. The area of the coke bed was about 3 by 10 feet. An attempt was made to place the coke as nearly uniformly about the electrodes as practicable.

The results of the periodical measurements of resistance have been plotted in Figs. 24 and 25, curves (2) and (5). Curves from specimens buried in clay are also given to aid comparision. In the case of the strip, as shown by curve (2), there is some reduction of resistance, but apparently not nearly as much as for the strip put down with salt. Moreover, the variation of resistance from time to time is obviously as great as in curve (1), although the high values noted on November 1 and December 1, 1915, are undoubtedly to be attributed to a loose lead. At any rate, on January 4, 1916, the lead was found detached from the strip and another substituted for it, so the dotted line connecting the points representing the values of resistance obtained on October 4 and January 4 probably nearly represents the actual resistance. In the case of the plate, on the other hand, the reduction of resistance is much greater than in that of the strip, being about 53 per cent, but with regard to uniformity of resistance the effect of the coke does not appear to be more marked here than above, since the ratio of maximum to minimum is 1.7, or the same as for the plate put down in clay.

Measurements made on the coke used in the experiments just described show its resistivity to be of the order of 130 ohms per cubic centimeter, or but a fraction of that of the average soil. This value was obtained on a sample that had been in the ground for more than a year. It was dug up, pounded fine in a mortar, tamped in a glass-lined iron cylinder in the same way as described for tests of the effect of salt on the resistivity of soils, and its resistivity measured with alternating current. It was then dried and its resistivity measured again, the result being practically the same. The resistivity was found to vary between wide limits with pressure and temperature, so the coke in the two conditions

was measured at as near the same temperature and pressure as practicable. The pressure was applied by means of a metallic piston, and was about 14 pounds per square inch. The temperature was a little higher than that of the room, which was 21° C, on account of the heating effect of the current which was allowed to flow for a short time before the readings were taken. The values obtained are to be considered only as showing that the resistivity of coke is very low in comparison with that of the soil, and that the difference in conductivity between wet and dry coke amounts practically to nothing.

When the resistivity was measured, the moisture content was also obtained, and found to be about 19 per cent, by weight, of the dry coke. The soil in which the sample was buried seemed to be quite saturated and must have contained more than 30 per cent moisture. The coke, therefore, had ample opportunity to become saturated. The weight of the packed dry coke was 70 pounds per cubic foot. The weight of the water per cubic foot of wet coke was 12.2 pounds. It was noted that the volume of the coke when dry was less than when wet. The shrinkage on drying was from 31 to 28.5 cubic inches, the volume in both instances being measured when packed and under pressure for the resistivity measurements. The total amount of water driven off was 0.22 pound.

From these data the function of the coke in reducing the resistance of ground connections is readily apparent. It is that of replacing a volume of earth of high resistivity surrounding the electrode with an equal volume of coke of low resistivity. The greater the volume of coke the greater the reduction of resistance, although not in the same proportion. Whether the coke is wet or dry makes but little difference. Moisture changes, in affecting the resistance of ground connections made with coke, act only on that part of the resistance contributed by the soil, but because the portion of the total resistance contributed by the soil is large in comparison with that contributed by the coke the effects appear to be practically as great, in percentage at least, as in ground connections made in clay. For example, take an electrode in earth having a resistivity of 5000 ohms per cubic centimeter which shows a resistance of 25 ohms to flow of current away from it. If enough coke is placed around it to reduce the resistance 40 per cent, the resulting resistance will be 15 ohms. Since the ratio of resistivities of coke to soil is about as 1:40, the portion of the resulting resistance contributed by the coke is about one-fortieth of that contributed by the earth which it replaces, or

0.25 ohm. The portion of the 15 ohms contributed by the soil is therefore $15 - 0.25 = 14.75$ ohms. Hence, moisture changes produce practically as large percentage changes as if the coke were not present. On account of its low resistivity, the coke bed constitutes virtually an extension of the electrode, and its distribution is for that reason of considerable importance. For the best results it should have a large area of contact with the soil in proportion to its volume.

The foregoing results do not agree in every respect with those of Sloss and Fish, and Ford, previously mentioned, but they do indicate that the benefits derived from the use of coke are not as great as has sometimes been stated to be the case. For instance, particular stress has been laid by some upon the uniformity of resistance obtained, but this statement is not supported by the tests because ground connections made with coke are seen to be almost as sensitive to changes in moisture conditions as those made in clay. There is, of course a considerable reduction of resistance, although this advantage is offset in large measure, at least, by the fact that it is in all cases necessary to excavate to get the coke in place. And in this respect it is at a disadvantage as compared with salt, which can be carried into the ground by burying it near the surface and flooding the hole with water, or allowing time enough for seepage of rain water to accomplish the same purpose. Coke and charcoal, however, do not have to be renewed, and in this respect present an advantage over salt.

The greatest disadvantage attending the use of either coke or salt is that touched upon in a previous paragraph, viz, an increased rate of corrosion of the electrode and consequent shortening of the life of the earth connection as compared with its life in normal soil, especially where galvanized iron is used. Just what this reduction in life may be can not at present be stated because of lack of data. In fact, experiments extending over several years would be necessary to obtain the desired information, but there seems to be no doubt in the minds of many that the reduction in life is considerable, coke in general being considered more detrimental than salt. Others state that the effects of salt on galvanized iron underground are negligible. In this connection it should be mentioned that the specimens described above showed no appreciable corrosion on superficial examination after being in the ground 14 months. Nevertheless, it is likely that the increase of corrosion due to the presence of salt will be considerable in its effects over a period of years, resulting in a material shortening

of the total life of the earth connection; and, moreover, the effects of coke may well be anticipated to be greater than those of salt. Copper, on the other hand, is much more resistant to corrosion than galvanized iron, and where long life of an earth connection with little attention is much to be desired copper should undoubtedly be used.

9. DISSIPATION OF ENERGY BY GROUND CONNECTIONS

For successful operation ground connections must in some cases be able to dissipate considerable amounts of energy without material changes in their resistances. An instance is afforded by an accidental contact between a high-voltage and a low-voltage circuit. Here the conditions may be such that the current flow through the ground connection is insufficient to operate the protective devices, and if it is it may continue almost any length of time before it is detected and the fault removed. In the meantime the rate of liberation of energy in the soil in the form of heat is proportional to I^2R, I being the current and R the resistance to its flow away from the electrode. A large part of this heat is absorbed by the soil water, and it is obvious that if the rate of its liberation at any point is high enough steam will be formed there and moisture thus driven into the neighboring soil or the atmosphere. An excessive current, therefore, is likely to cause drying of the earth immediately surrounding the electrode and a consequent great increase of resistance.

In the course of this investigation some experiments were conducted in collaboration with the Potomac Electric Power Co., of Washington, D. C., which show the behavior of ground connections when subjected to a greater rate of liberation of energy than they can continuously care for. These experiments were made on five specimens of 0.75-inch galvanized-iron pipe driven to a depth of about 10 feet in soil consisting of a fill containing cinders, ashes, and other refuse. They were put down by first driving a pointed 2-inch pipe to a depth of about 5 feet, pulling it out, and driving the smaller pipe in the bottom of the hole. Before driving the smaller pipe, however, about 2.6 gallons of 15 per cent salt (NaCl) solution was poured in. The resistances were measured and found to be as follows:

TABLE 10

No. of specimen	1	2	3	4	5
Ohms	12.4	11.2	15.4	7.6	16.7

In the first set of experiments 1100 volts were impressed upon Nos. 1 and 4 in series. The current at the beginning was 61 amperes. At the end of five minutes No. 1 began to steam. It soon stopped, however, and No. 4 commenced. At the end of 16 minutes the current had decreased to 24 amperes, with the greater part of the energy being consumed by No. 4. The soil nearest the pipe glowed and gave off clouds of smoke, due most likely to burning humus. A measurement of voltage between the pipe and a spot on the ground about 1 foot away showed a difference of potential of 885 volts. A similar measurement on No. 1 showed a difference of potential of only 30 volts. The current fluctuated with great rapidity after the earth connection began to smoke, making accurate measurements very difficult. Two or three buckets of water were poured on the ground around No. 4, but produced no permanent effect. At the end of the experiment the ground was flooded with water from a hose.

The following day the test on Nos. 1 and 4 was repeated. This time no disturbance occurred around No. 4, but within 10 minutes No. 1 began to steam, and in 52 minutes the current had decreased from 80 to 30 amperes. The soil immediately surrounding the pipe finally glowed and gave off clouds of smoke in the same way as described for No. 4 in the preceding paragraph. The current in No. 1 was then discontinued, and Nos. 4 and 5 connected in series. In 36 minutes No. 5 began to smoke, and the current had decreased from 35 to 4 amperes. At the conclusion of this series of experiments about 6.6 pounds of salt was buried in the soil around each specimen.

Three months later a similar test was made on Nos. 1 and 5, immediately following a heavy rain. A current of 60 amperes at 1100 volts was maintained for 40 minutes, but no increase of resistance became apparent, although No. 5 gave signs of failure by steaming. The circuit was broken at the end of 40 minutes to avoid overheating of the transformers. The effect of the salt and the increase of moisture due to rainfall is made evident by the resistances, measured before beginning the test, which show a marked decrease from the values obtained at the time of the first experiment, and were as follows:

TABLE 11

No. of specimen	1	2	3	4	5
Ohms	6.42	6.50	8.80	3.83	11.4

The most obvious fact brought out by these experiments is that mentioned above, viz, that if a ground connection is required to dissipate energy at an excessively high rate drying of the soil will occur, with a great increase of resistance. But this increase of resistance is not permanent; the original conductance is recovered in a short time. In addition it is apparent that the relative capacities of ground connections to dissipate energy are not reliably indicated by their resistances, at least not for electrodes of the same size and shape. For as indicated in the first experiment, No. 4 was first to fail, although its resistance was only a little more than half that of No. 1. Finally, the magnitude of the rate at which a ground connection of the dimensions of those described above can dissipate energy continuously without an increase of resistance may be estimated from the results of the last test. The current was 60 amperes, the resistance of No. 1 at the start 6.42 ohms, and of No. 5, 11.4 ohms. Hence, the value of I^2R for No. 1 is about 23 kw and for No. 5 about 41 kw. The latter gave signs of failure, but as far as could be told No. 1 would have carried 60 amperes indefinitely. It is possible, however, that after a number of hours an increase of resistance would have taken place. On the other hand, several tests showed that dissipation of energy at a rate of 3 to 5 kw produced no effect on any of the specimens beyond a slight decrease of resistance due to increase of temperature. It appears, therefore, that it may safely be assumed that the maximum rate at which a ground connection made by driving a pipe to a depth of 10 feet in moderately salted moist soil can dissipate energy continuously without an increase of resistance lies somewhere between 5 and 20 kw. Nevertheless, if there is a possibility that a ground connection of this kind will ever have to dissipate energy at a rate of more than 8 or 10 kw it is perhaps best that an investigation be made to determine whether it will meet the requirements.

The probable reason why the capacity of a ground connection to dissipate energy is limited appears from the following considerations: When current is flowing the rate of liberation of heat is, in general, greatest in the layer of earth nearest the electrode, for it is there that the current density is greatest, and the rate of liberation of heat varies as the square of the current density. As a consequence water evaporates more rapidly from this layer than elsewhere, and, if it is not replaced at a rate equal to that

at which it is driven away, drying of the soil will follow, causing an increase of resistance. On the other hand, if it is replaced at the same rate as it is driven away current can flow indefinitely without an increase of resistance. Now, the only way in which the evaporated moisture can be replaced is by water flowing in from the surrounding region by capillary action. This, of course, takes place, but there is a definite limit to the rate at which water can move through soil by this means. Hence, if the current flow through a ground connection is gradually increased, a point will ultimately be reached at which heating drives off moisture faster than it is supplied, with results as described in the preceding paragraphs.

No tests have been conducted on ground connections consisting of electrodes of different forms under different conditions, but it is readily apparent that the maximum capacity of a ground connection made with an electrode of any form to dissipate energy may differ widely with the kind of soil in which it is situated, and also vary from time to time for the same soil. Among the factors which affect it may be named the moisture content, the rate at which moisture moves by capillary action and the distance which it will cover, the surrounding temperature, and the size of the electrode. It is practically impossible to separate some of these various factors, or control them experimentally, and for that reason laws or performance records under a variety of conditions from which the maximum capacity of a ground connection to dissipate energy may be predicted with any degree of exactness are not readily obtainable. If this characteristic of a ground connection must be known it is nearly always necessary to make a test in each case. It may be stated, however, that the greater the moisture content of the soil the greater the rate at which energy can be dissipated. Moreover, with a given moisture content, this rate will be greater in soils of fine texture than in those of coarse texture, because the former carry moisture at a greater velocity and over greater distances by capillary action than the latter. The surrounding temperature may also produce a marked effect, for the lower it is the greater the rate at which heat will be carried away by radiation and conduction.

With regard to the size of the electrode, it is easily demonstrated, for certain special cases at least, that the larger it is the greater the rate at which energy can be dissipated without too

rapid evaporation of moisture. In order to do this suppose an electrode of any shape to be buried in the ground. Let

A_1 be the surface area of this electrode in contact with the soil,
R_1 the resistance to flow of current away from it,
I_1 the total current, and
i_1 the average current density.

The rate of dissipation of energy will be $I_1^2 R_1$.

Suppose the dimensions of the electrode to be increased. Let

A_2 then be the surface area in contact with the soil,
R_2 the resistance to flow of current,
I_2 the total current, and
i_2 the average current density.

If the rate of dissipation of energy in the two cases is the same, $I_1^2 R_1 = I_2^2 R_2$ ..... (a). Evidently $i_1 A_1 = I_1$, and $i_2 A_2 = I_2$. Substituting in (a), $i_2 = i_1 \frac{A_1}{A_2} \sqrt{\frac{R_1}{R_2}}$.

Now, as mentioned heretofore, in the case of a circular plate embedded to a depth equal to one-half its thickness in the ground the resistance is $R_1 = \rho/2d$, where d is the diameter of the plate and ρ the resistivity of the soil. If the diameter is increased by a factor n, $R_2 = \rho/2nd$. Also $A_1 = \pi r^2$ and $A_2 = \pi n^2 r^2$. From (a), therefore, $i_2 = i_1 \sqrt{\frac{n}{n^2}}$, in which, since $n > 1$, the factor $\sqrt{n}/n^2$ is always less than unity, and $i_2 < i_1$.

In the case of a driven pipe, $R_1 = \frac{\rho \log_\epsilon \frac{2L}{d}}{\pi L}$, where L is twice the length of the driven pipe, and d its external diameter. If the length of the pipe is increased by a factor n, $R_2 = \frac{\rho \log_\epsilon \frac{2nL}{d}}{\pi nL}$. Also $A_2 = nA_1$.

$$\therefore i_2 = i_1 \sqrt{\frac{\log_\epsilon \frac{2L}{d}}{n \log_\epsilon \frac{2nL}{d}}}$$

Here, since $n > 1$, the denominator of the fraction under the radical, is greater than the numerator, so the value of the fraction is always less than unity. Hence $i_2 < i_1$.

In the case of a buried strip, as shown by measurements previously discussed, increasing the length causes practically a propor-

tional inverse change in the resistance. That is, if the length is increased by a factor n, it follows that $A_2 = nA_1$ and $R_1 = nR_2$. Whence $i_2 = i_1 \overline{n}/n$ and $i_2 < i_1$.

It appears, therefore, that an increase in the size of an electrode, at least of those shapes commonly used in practice, results in a decrease of the average current density for the same rate of expenditure of energy. And, since the rate of liberation of energy in the form of heat at any point is proportional to the square of the current density, the tendency toward drying of the soil at the surface of the metal is diminished. Or, to put it in other words, an increase in the size of an electrode permits an increase in the rate at which energy can be dissipated without drying the soil and increasing the resistance.

In previous paragraphs the fact was mentioned that the rate of liberation of heat is greatest in the soil nearest the electrode, the rate being proportional to the square of the current density, and also to the resistivity. This being the case, if the resistivity is reduced by salting or otherwise, the capacity of the ground connection to dissipate energy will be increased, because the tendency toward drying of the soil at the surface of the electrode will be diminished. For example, take a driven pipe. A cylinder of earth 2 feet in radius and coaxial with the pipe may be estimated as contributing about 50 per cent to the total resistance. If a current is flowing, half of the total amount of heat will be liberated in this cylinder. Now, if the cylinder is impregnated with salt to a sufficient degree to make the resistivity one-fifth normal the portion of the total resistance contributed by it will be only 16.6 per cent instead of 50 per cent. Furthermore, if the same amount of heat is liberated as in the first case, the portion of the total liberated in the cylinder will also be 16.6 per cent instead of 50 per cent. Salting thus causes the distribution of heat liberation to be shifted in such a way that more of the heat is developed at a distance from the electrode than where salt is not used, with a consequent improvement in the facility with which it can be taken care of. Tests by Creighton [35] indicate that by thorough salting the capacity of an earth connection to dissipate energy may be increased by several times. The foregoing statement applies in greater or less degree to any treatment of the soil surrounding an electrode which decreases its resistivity.

[35] General Electric Review, 15, p. 12 and 66.

10. POTENTIAL GRADIENTS

When current flow takes place through a ground connection, a potential gradient exists in the surrounding surface of the ground. This potential gradient decreases on receding from the electrode and practically disappears at a distance of a few meters. It is of importance in that it may be a source of danger to persons and animals. In order to obtain data on its character in the vicinity of driven pipes when subjected to heavy current flow a test was made on some of the specimens previously described. This test consisted in passing a 60-cycle alternating current at constant

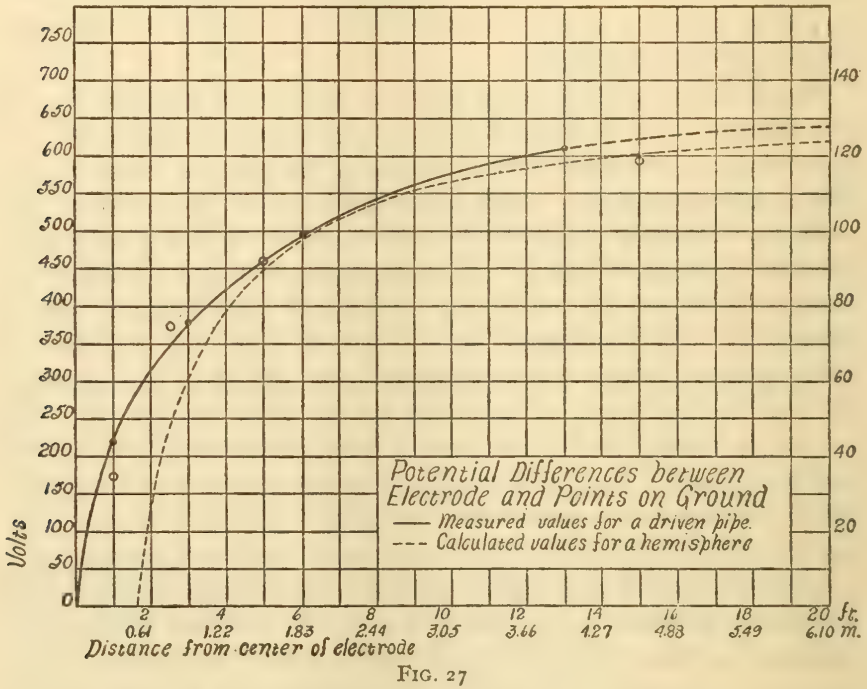

FIG. 27

voltage through the ground connection and measuring the potential differences between the pipe and points on the surface of the ground at various distances away. Plotting these potential differences as ordinates and distances as abscissæ gives a curve the slope of which at any point is proportional to the potential gradient. The results from a specimen which is more or less typical are shown in Fig. 27. This specimen is No. 1 of Table 10, Nos. 1 and 4 being in series in this particular case, with 232 volts impressed for one set of readings and 1100 volts for another. The total voltage was, of course, shared by the specimens very nearly in direct proportion to their resistances, since they were 104.5 feet

apart. Hence, the part taken by No. 1 can be calculated from the current and the resistance. The resistance was found to be 11.6 ohms, and the current at 12.5 amperes at 232 volts and 59 amperes at 1100 volts. The voltage impressed upon No. 1, therefore, was 143 in the first instance and 684 in the last. With the lower voltage the current was left on continuously, but with the higher voltage the current was allowed to flow only while readings were being taken to avoid change of temperature and a consequent change of resistance. Nevertheless, a slight change occurred, and there was a considerable change from the preceding day, for then, as shown in Table 10, No. 1 had a resistance of 12.4 ohms. In Fig. 27 the potential differences at the lower voltage are indicated by circles and refer to the scale at the right-hand margin, whereas the potential differences at the higher voltage are indicated by dots and refer to the scale at the left-hand margin.

For measuring the potential differences a double-scale voltmeter (0–150, 0–300) was used, and also a voltmeter (0–30) with a potential transformer. The resistance of the 150-volt coil of the voltmeter was 2044 ohms, and of the 300-volt coil 4083 ohms. The impedance of the high-voltage coil of the transformer, with the 0–30 voltmeter connected across the low-voltage terminals, was about 87 000 ohms. At each point of measurement some earth was loosened, water poured over it, and contact made with the ground by means of a brass disk, 7 inches in diameter, which was pressed into the wet soil.

The resistance to flow of current from the disk into the earth was not great enough seriously to interfere with the readings, that is, the reading recorded in each instance is not much less than the actual voltage. For, as shown below, the average resistivity of the soil appeared to be about 3600 ohms per cubic centimeter, and at the surface, on account of the admixture of coal dust, ashes, and other refuse, was probably less; 3000 ohms may be assumed as a fair value. Moreover, as indicated under resistance of ground connections, the resistance to flow of current away from such a disk is expressed by $R = \rho/2d$, where ρ is the resistivity of the soil and d is the diameter of the disk in centimeters. Hence, $R = 3000/2 \times 17.8 = 84$ ohms, a value which in this case can be neglected in comparison with the resistance of the voltmeter or the impedance of the transformer, since its effect on but few readings is sufficient to cause an error of as much as 4 per cent. In no

instance was difficulty experienced in repeating results with a fair degree of accuracy, especially at the higher voltage.

In Fig. 27 there is also plotted a curve showing potential differences calculated for a hemispherical electrode of a radius numerically equal to the combined electrostatic capacity in free space of the pipe described above (No. 1, Table 10) and its image, and embedded with its plane surface flush with the surface of the ground in uniform soil of the same resistivity as the average of that surrounding the pipe. The electrostatic capacity, and consequently the radius of the hemisphere, are seen from Table 1 to be 49.6 cm. The resistivity of the soil from $\rho = 2\pi CR = 2 \times 3.1416 \times 49.6 \times 11.6 = 3600$ ohms per cubic centimeter. The resistance to flow of current away from the hemisphere is therefore the same as for the pipe, or 11.6 ohms. Also, with 684 volts impressed the current will be 59 amperes. The potential differences may now be calculated as follows: Let r_1 be the radius of the hemisphere, in this case 49.6 cm, r the distance from its center to any point on the ground, dr the thickness of an elementary shell of earth concentric with it, I the total current flowing, E the potential applied, R the resistance, and ρ as above. The resistance to flow of current through the shell will be dR. Now $dR = \frac{\rho dr}{2\pi r^2}$ and $dE = IdR = \rho I dr/2\pi r^2$. Whence $E_r = \frac{\rho I}{2\pi}\int_{r1}^{r}\frac{dr}{r^2} = \frac{\rho I}{2\pi}\left[1/r_1 - 1/r\right]$. Substituting for ρ and I, $E_r = \frac{3600 \times 59}{2 \times 3.1416}\left(\frac{1}{r_1} - \frac{1}{r}\right) = 33\,800\left(1/r_1 - \frac{1}{r}\right)$. From this formula E_r has been calculated for different values of r and plotted in Fig. 27. The resistivity of the metal composing the electrode is neglected.

The two curves exhibit a marked degree of similarity. In addition, such measurements as have been made indicate that in the majority of cases measured values and calculated values will fall in close relation to each other, and for these reasons the curve for the pipe can doubtless be regarded as fairly typical of pipes driven in normal soil, at least for pipes up to 10 feet in length. At the same time, however, it should be stated that in many cases there will be wide deviations from the calculated curve, the extent of the deviations depending upon the condition of the soil in the immediate vicinity of the pipe, and also upon the firmness with which it is packed against the metal. Moreover, as the length of the pipe increases there is a tendency for the

curve of potential differences to become flatter and approach a curve represented by the expression. $E_r = \frac{\rho i}{2\pi} \log_e \frac{b}{a}$. This expression applies to a pipe or rod extending into the earth to such a depth that current flow away from it at the top is radial.

The quantity i is current per unit length of the electrode, a the radius, and b the distance from the axis to any point on the ground.

On the other hand, from the closeness with which the circles representing potential differences at 143 volts fall with respect to the curve through the dots, it is evident that the shape of the curve will be the same whatever the voltage. With the aid of this curve, therefore, and the resistance and current flow, a rough idea may be obtained in any given example of the potential differences between the pipe or earth wire leading to it and near-by points on the ground. For instance, if the resistance is 25 ohms and the current 6 amperes, the total voltage will be 150. This is nearly 0.22 of 684 volts. Therefore, upon multiplying this factor, or 0.22, into the ordinates of the curve in Fig. 27, it is seen that at a distance of 2 feet the potential difference between earth wire and ground will be about 66 volts; at 4 feet about 92 volts, and so on. As the current flow increases the potential differences will also increase in the same proportion, unless there is marked heating near the electrode. In this event the increase of temperature will cause the resistivity of the soil near the electrode at first to decrease, which in turn will cause the potential differences between the pipe and points near by also to decrease, but as heating proceeds to such a degree that drying of the soil occurs an opposite effect is produced. The resistivity increases enormously, which causes the potential differences in turn also to increase. For example, when No. 4 failed under too great a rate of dissipation of energy the difference of potential between the pipe and a point on the ground 1 foot away reached a value of 885 volts, instead of 100 or so as it would have if drying of the soil had not occurred. Consequently, in making earth connections in practice, careful consideration should be given to the possibility of failure through excessive flow of current.

At this point it may be mentioned that salting has an important effect, not only upon the capacity of a ground connection to dissipate energy, but also upon the potential gradient, especially in the vicinity of driven pipes. To demonstrate this effect an

experiment was made upon a 0.75 inch pipe driven to a depth of 5 feet in rather stony clay soil, with similar pipes driven at various distances away from it to serve as contacts in measuring potential differences. The first step taken was to impress 145 volts upon the driven pipe in series with a water pipe ground. The current was found to be 2.05 amperes, and the resistance, therefore, was 70.6 ohms, which corresponds to a soil resistivity $\rho = 2 \times 3.1416 \times 28 \times 70.6 = 12\,450$ ohms per cubic centimeter; that is, if the resistance of the water pipe ground, which was about 1 ohm, is neglected. The potential differences were measured with a voltmeter having a range of 150 volts and a resistance of 1996 ohms. The resistance to flow of current away from each driven pipe serving to make contact with the earth was known so corrections were made to the voltage readings, this correction being about 4 per cent. The results are shown plotted in Fig. 28, each potential difference being represented by a dot.

The next step was thoroughly to salt the specimen. A hole about 2 feet in radius and 1 foot deep was dug around it, 65 pounds of salt poured in, and covered with earth. At intervals of two or three days the soil was flooded with water to dissolve the salt and carry it deeper into the ground. The potential measurements were then repeated. With 145 volts impressed the current was found to be 6.6 amperes. The resistance, therefore, was 22 ohms, or about 31 per cent of its original value. This reduction is mostly due, of course, to the effect of the salt in lowering the resistivity of the soil near the pipe, but is also in small part due to the water used to dissolve the salt and to a rainstorm which increased the moisture content in the entire region. Nevertheless, any changes in the shape of the curve showing potential differences may be nearly all attributed to the salt, because a uniform change of resistivity due to rainfall would have no effect beyond decreasing the total resistance, and as the soil was quite moist to begin with, the water poured around the pipe would not produce an effect on the resistivity of the soil in any way comparable with that produced by the salt. The results are plotted in Fig. 28, the potential differences being represented by circles.

In Fig. 28 there are also plotted calculated potential differences for a hemispherical electrode in the same way as in Fig. 27. The radius of this hemisphere is taken as 28 cm (0.918 feet), or numerically equal to the combined electrostatic capacity in free space of the pipe and its image in the surface of the ground, as shown by Table 1. When buried in soil of resistivity equal to 12 450 ohms

per cubic centimeter, the resistance will therefore be the same as for the pipe, or 70.6 ohms, and with 145 volts impressed the current will be 2.05 amperes. Substituting these quantities in the formula $E_r = \frac{\rho I}{2\pi}\left[\frac{1}{r_1} - \frac{1}{r}\right]$, results are obtained for different values of r, which correspond to the upper broken-line curve. On the other hand, the lower broken-line curve represents potential differences calculated on the assumption that the soil surrounding the hemisphere to a distance of 2.9 feet from its center is salted in the same way as described for the pipe. The quantity of salt placed around the pipe was sufficient to make nearly a 2 per cent solution of the soil water in a cylinder the length of the pipe, concentric with it, and about 2 feet in radius, if the moisture content is taken as 30 per cent. The soil was quite moist, so it is likely that this value is about right. From Fig. 26 it is seen that adding 2 per cent salt to the soil moisture decreases the resistivity by about 13 times. Assuming this to be the case for the pipe, the resistivity of the soil for 2 feet from it is roughly 1000 ohms per cubic centimeter. Beyond that it is greater, but because of the rain must be taken as less than 12 450, as indicated above. The calculation will come out about right if it is considered to be 10 170 ohms per cubic centimeter. That is, with ρ=1000 ohms per cubic centimeter to a distance of 2.9 feet from the center of the hemisphere, and 10 170 ohms per cubic centimeter beyond that, the total resistance to flow of current will be 22 ohms, and with 145 volts impressed the current will be 6.6 amperes. Substituting in the formula for E_r results are obtained which correspond to the lower broken-line curve of Fig. 28. The similarity between the curves representing calculated and measured values is even more marked than in Fig. 27.

The effect of the salt in changing the potential gradient near the pipe is practically that which might be expected from previous study of its effect on the resistivity of soil. In the main the change may be regarded as beneficial, although as far as danger to animals is concerned there is scarcely any improvement. For if a large animal, such as a horse, were standing near the pipe with front feet 1.5 feet from it the rear feet would be approximately 5 feet farther away. From Fig. 28 the potential difference between these two points is seen to be about 35 volts before salting, whereas afterwards it is about 70 volts. Hence, the application of salt appears to cause an increase in the danger to animals, but with regard to persons the danger is lessened, be-

cause injury is most likely to occur through touching the pipe or earth wire, and salting causes a marked reduction in the potential differences between the pipe and points within reaching distance of it. The greatest advantage, however, is that mentioned heretofore, viz, reduction of resistance, which facilitates the operation of protective devices.

With regard to plates, or other electrodes buried beneath the surface of the ground, the potential gradient is not nearly so important a matter as in the case of pipes or electrodes which are accessible. For with the former the region of greatest potential

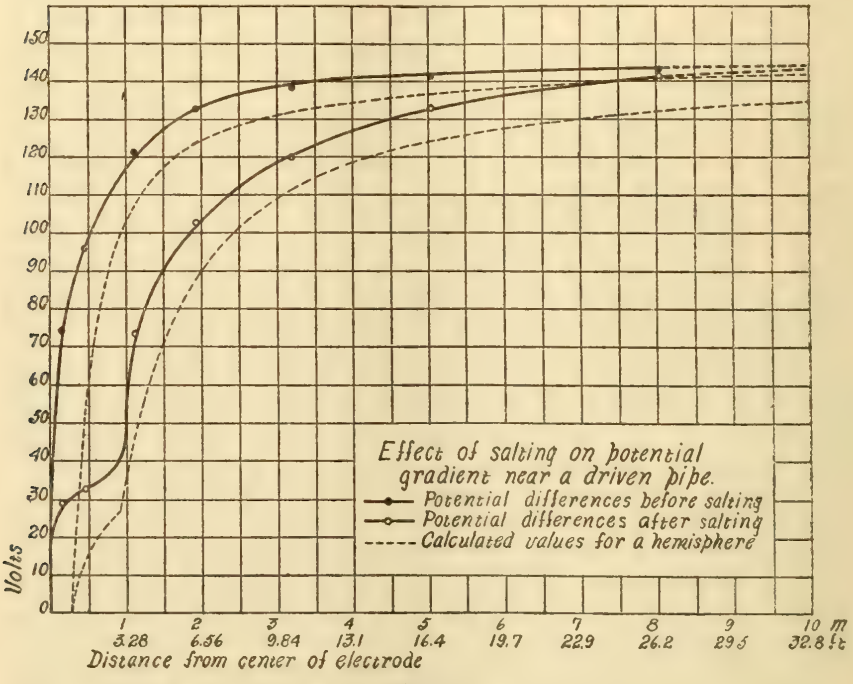

FIG. 28

gradient is underground and out of reach of persons, whereas that found at the surface is not likely to be of much moment. For instance, with a plate buried at a depth of about 6 feet, having a resistance of 2.2 ohms, and carrying a current of 100 amperes, the potential gradient immediately over the plate proved to be about 4.5 volts per foot.[36] A potential gradient of this magnitude would present very little danger to either persons or animals. Electrodes at lesser depths, of course, might show greater values, but only in extraordinary cases would they be sufficient to be of importance.

[36] Sparks, Journal I. E. E., 53, p. 401.

The greatest danger from ground connections made with electrodes buried beneath the surface arises from the high potential differences which may exist between the earth wire and points within reaching distance of it when current is flowing. In the case just mentioned this was 150 volts, the total voltage, being 220. With the earth wire well guarded, however, and every part of the ground connection mechanically strong, as described below, the likelihood of injury from it is very small.

V. MECHANICAL CONSTRUCTION OF GROUND CONNECTIONS

Substantial construction is one of the first considerations in making ground connections of any type and should never be sacrificed to expediency. For if grounding is poorly done it might in most cases as well not have been done at all; ground wires break, clamps come loose, electrodes corrode away, and even though repairs are constantly attended to, the protection afforded may be inadequate and unreliable. Moreover, the presence of a ground connection of any kind engenders a feeling of security which is false unless the materials and workmanship are of the best. Too much emphasis can hardly be laid upon the necessity for carefulness in this particular feature of electrical practice.

1. DRIVEN PIPES

In driving pipes difficulties are sometimes encountered, and as a consequence the work is not uncommonly slighted. The chief difficulties are presented by stones and crumpling of the pipe under the hammer. In some localities stones are so numerous as to prevent driving altogether, but very stony ground can be penetrated by first driving a steel bar with a tempered point. The bar can stand almost any amount of hammering, and when it is removed the pipe can be driven in the same place with comparative ease. By this means a good ground connection may in many cases be obtained where otherwise the operation might result in a waste of material. The size of the bar should be somewhat less than that of the pipe, because if the hole is made too large some time may be required for the soil to settle, and in the meantime the resistance is not unlikely to be so high as to be unsafe.

With a bar driven 10 to 12 feet in the ground considerable force is necessary to remove it, and where many ground connections

are to be made a great deal of time can be saved by making adequate preparations in advance. The force required may be estimated at from 3 to 4 tons. For applying it a 3-ton differential pulley will probably be found satisfactory, although other means may be used with good results; for instance, a lever of the proper dimensions, a lifting jack, or a chain and fulcrum with a team of horses or a motor truck. The bar may well have a heavy hook welded on near the top for attaching the chain in pulling. The pull should be as nearly vertical as practicable to avoid bending the bar or widening the hole.

In soft ground, however, or even rather hard ground where there are few stones, pipes may readily be driven to the required depth without the use of a bar. The greatest trouble which will be met with in this case, and also in stony ground, is crumpling and bending at the upper end. With ordinary galvanized iron pipe this is not easy to avoid. Nevertheless, if the hammering is not severe a coupling screwed on a threaded end as far as it will go will in some cases serve very well to prevent it, but these couplings split easily, or the pipe may break off in the thread. On the other hand, if heavy hammering is required, a more satisfactory method is to drive 4 to 6 inch lengths of lap-welded steel conduit over the end of the pipe. If the end is threaded or otherwise a little reduced in size, a 1-inch conduit can be driven over a 0.75-inch pipe or a 1.5-inch conduit over a 1.25-inch pipe. This conduit is tough and will be of great assistance in preventing battering. But where a great deal of pipe is to be driven which is all of the same size the most satisfactory method is to make a cap of mild steel similar to that shown in Fig. 29. The shank *A* is made to fit rather snugly on the inside of the pipe, and the circular slot *B* is of a width but little greater than the wall thickness. The farther *A* extends into the pipe the more effective it will be in preventing bending. Such a cap will serve for a great many pipes before wearing out.

In general it will be found that the medium sizes of pipe drive better than either the smaller or the larger sizes, as they can withstand far more hammering than the smaller sizes and at the same time do not require as much of it as the larger ones. In fact, in stony ground it is extremely difficult to drive a 2 or 2.5 inch pipe to the requisite depth even though a bar is driven in advance. For general purposes, therefore, the 1 or 1.25 inch sizes may be considered preferable. They can be driven with either square or

flattened ends, but neither seems to present a marked advantage over the other. The use of extra heavy pipe is to be recommended on account of its greater strength to resist the effects of driving and also the greater amount of metal to resist corrosion.

After a pipe is driven the crumpled part should be cut off near the surface of the ground with a hacksaw, the exposed end threaded, and a brass casting screwed on which is made with a lug to which the earth wire can be soldered, or an ordinary coupling can be used at the surface of the ground and the pipe extended upward 8 or 10 feet if beside a pole or building. The joint between wire and pipe is thus removed from the possibility of mechanical injury. Where a number of pipes are to be connected together, pipe and ordinary fittings may be used, or brass castings and copper wire. With either the connections can best be placed underground, where they will be better protected from breakage than if exposed. Wires should be laid slack for the reason that if they are disturbed they are less likely to be broken.[37] Joints, or places where the galvanizing has been impaired, should be well daubed with hot pitch or tar and wrapped with cloth, or otherwise protected from soil corrosion. The brass castings just mentioned can be purchased in the market. In place of them, however, a good joint between wire and pipe can be made by driving a wooden plug into the pipe until it is 3 to 4 inches below the top, inserting the wire and pouring the hole full of melted lead. Where salt is used it is advisable to dig a hole around the pipe to a depth of 1 foot or so, dump in the salt, and cover it with earth. With the salt buried in this way there is no chance of its being carried away by surface water, and its proper distribution through the soil is assured. To hasten distribution at first, water may be used, but this should not be overdone, as a large part of the salt may be washed away. As much dependence as practicable should be placed upon natural diffusion.

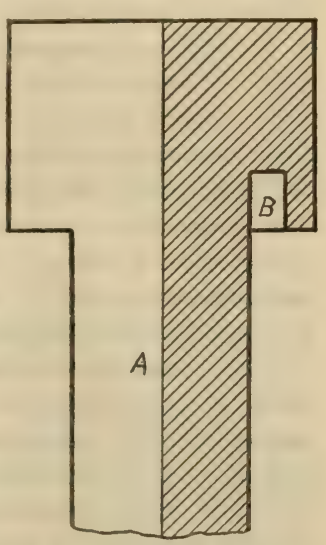

FIG. 29.—*Cap for driving pipe*

[37] See Rule 93*d*, Appendix II.

2. PLATES

In selecting materials for ground plates much depends upon the length of life required of them. If they are intended to be practically permanent, copper, of course, is about the only metal commercially available which will serve the purpose, although galvanized iron, will last for a number of years, even where salt is used, and is much less expensive. The thickness of a plate has very little to do with the resistance to flow of current away from it, and is therefore determined solely by mechanical considerations and the extent of the corrosion that is likely to take place. In general Nos. 14 to 18 gauge sheet metal will be found satisfactory in either copper or iron. With iron, however, because of its greater susceptibility to corrosion, heavier sizes may be used to slight advantage on account of the greater amount of metal, but it should be remarked that it is upon the galvanizing that the most of the life of such a plate depends. Hence, none but the best quality of galvanized sheet should be considered. Cast-iron plates do very well in some cases, being especially resistant to corrosion in ordinary soils. But, on the other hand, any of these materials may corrode very rapidly if exposed to some soils or to seepage from dumping places.

With plates the connection between electrode and earth wire must be made underground. This puts the joint out of reach of inspection and precautions are therefore necessary to make it last as long as the plate does. A procedure which has in many instances been recommended, and which is, perhaps, as good as any, is to use a heavy earth wire, or preferably a strap of metal, which can be riveted and then soldered, the strap extending a foot or so over the surface of the plate. After the soldering is done it is advisable thoroughly to clean the metal around the joint and coat it with tar or pitch to prevent corrosion. If the plate and earth wire are of different metals, this corrosion, due to galvanic action, may be considerable. If both are of copper, however, there is little danger of damage from this cause.

When plates are buried, care should be taken to make as good contact with the soil as practicable, for the effectiveness of the ground connection depends to a considerable extent upon the thoroughness with which the earth is packed against the metal. If the plate is placed on edge, no particular care in this respect is necessary; tamping on each side of it is sufficient. But if it is laid flat and the ground is stony, all of the stones should be removed

from the bottom of the hole, and, whether the ground is stony or not, the soil upon which the plate is to rest should be loosened to a depth of several inches. With this bed of loose earth, and the hole filled and rammed, good contact is likely to be obtained. Otherwise, the plate may rest on lumps and in that way make contact with the ground only in spots. It is also to be recommended that all stones be removed from the immediate vicinity of the plate whether it is placed on edge or flat, because, as previously mentioned, they are of high resistivity, and many of them nearby will affect the resistance to a marked degree. If salt is considered necessary, it can be worked into the loose soil around the plate. It can be renewed by burying it in much the same way as described above for pipes, and allowing natural diffusion to distribute it through the region below. Where coke is used, no particular care need be exercised beyond ramming it into the bottom and sides of the hole to insure good contact between coke and soil. It may be well to loosen the soil before putting in the coke, for better contact can thus be made.

3. STRIPS

The making of earth connections with strips involves nothing radically different from the process of making them with plates. The same kinds of metal may be used and for the same reasons. Joints may also be made in the same way, but since they are likely to be near the surface of the ground it may be well to protect them, not only against corrosion, but also against mechanical injury, by embedding them in concrete. Where the joints to be protected are those between strips and down conductors, or earth wires, the concrete should be flush with the surface of the ground and of sufficient volume to prevent its being easily moved, say a cylinder 8 to 10 inches in diameter and 1 foot long. It is true, of course, that the strip can be brought out of the ground at the point where it is attached to earth wires, which limits the possibility of corrosion, but at the same time this exposes the joint to mechanical injury. On the whole it seems better to keep such joints beneath the surface and protect them with concrete. In fact, this is a desirable means of protecting joints of any kind made underground which may be subject to galvanic action in the presence of moisture or be in need of mechanical reinforcement.

4. WATER PIPES

Where connection is to be made to a cast-iron pipe line with bell and spigot joints the most satisfactory method is probably that

prescribed by the National Fire Protection Association. This method consists in drilling a hole in the bell, tapping it, and screwing in a brass plug to which the earth wire is soldered. The joint thus made requires only a reasonable amount of labor and is permanent, especially if the surface of the plug and pipe in the immediate vicinity is heavily coated with pitch or something else to prevent corrosion. On the other hand, if connection is to be made to a service pipe which can be drained of water the wire can be wrapped several times around it and soldered, or a fitting can be utilized by screwing a plug into it and soldering the earth wire to the plug in the same way as described for bell and spigot joints. But if the pipe can not be drained conveniently the next best thing is a clamp to go around it, with a lug to receive the earth wire. To insure high conductance all scale and rust should be thoroughly removed before the clamp is put on. The pipe and clamp may also be treated with one of several amalgams now obtainable which are designed for the purpose of making good electrical connection between metallic surfaces which can not be soldered.

The selection of a clamp for attaching wires to service pipes requires some care in order to obtain a device that will maintain permanent contact. There are many clamps on the market, but such of them as have been examined at the Bureau of Standards appear to be of flimsy construction. The most of them consist of a copper strip not thicker than No. 20 gauge and about 0.75 inch wide, which encircles the pipe and is held by a set screw or small bolt passing through holes punched in the copper. Drawing the screw to a sufficiently firm grip puts too great a stress on the metal, and, in fact, strains it to such a degree that good contact is difficult to maintain. Moreover, in some cases lugs for the earth wire are not provided; one end of the copper strap is simply bent to the required shape. In view of these facts more substantial construction of clamps seems necessary. The metal used should be much thicker, say about No. 8 gauge, and a lug for the bolt should be riveted to each end of the strap. There should also in every case be a lug for the earth wire put in such a position that tightening the bolt results in a firm and permanent electrical contact.

The place at which it is desirable to make connection to service pipes must also be considered. In general, it may be stated that it should be so chosen that there is the least likelihood of the pipe being disconnected between the point at which the earth

wire is attached and the water main.[38] Moreover, where the water meter is placed in the basement of a building the point of attachment should be on the street side of the meter. Or, if the meter is located in a well or manhole under the sidewalk or street, a jumper, consisting of a wire as large or larger than the earth wire, should be placed around it. The necessity for these precautions arises from the fact that plumbers in making repairs may disconnect the pipe and destroy the effectiveness of the earth connection. Also, it is the practice of some water companies to remove water meters when buildings are vacated. It is desirable, however, to maintain the ground connection at all times, particularly if the circuit to which it is attached serves other customers in the vicinity, and the contingency presented by the removal of the meter can best be guarded against by shunting it with a heavy wire.

5. GROUND WIRES

The minimum allowable size of ground wires is determined principally by mechanical considerations, for they are more or less liable to mechanical injury, and must therefore be strong enough to resist any strain that is likely to be put upon them. The general practice in electrical construction is to place the minimum size at No. 6 copper, particularly for grounding circuits carrying current. This size is also specified in most codes of rules for the same purpose. The extent to which No. 6 is adhered to as a minimum size under all conditions is indicated by correspondence with electric companies.[39] In all, 418 companies were heard from. Four reported as using wires smaller than No. 6, 152 made no answer, while 262 reported as using No. 6 or larger. Hence, in view of the general use of No. 6 as a minimum size, it seems that it can be taken for granted that it is quite satisfactory, especially as there are no reports to the contrary. On the other hand, for earthing frames of machines and other noncurrent-carrying parts of electrical equipment it may in some cases be permissible to use smaller wires if they can be put where they are out of the way of possible damage. These smaller sizes, however, should be used only under certain conditions. For instance, if a small motor is connected to a low-voltage line which is already grounded for protection against high voltage, it is desirable also to ground the frame of the motor, but it is not so important a matter as it would be if the circuit from which energy is taken

[38] See rule 95*a*, Appendix II.

[39] This correspondence is summarized in Appendix I.

were insulated. Under such conditions breakage of the ground wire is not likely to be so serious. Consequently the ground wire used for the frame in this case, and also in all similar cases, may be smaller than No. 6, provided it is of sufficient current-carrying capacity, but it does not seem safe, even under such circumstances, to use wires smaller than No. 14.[40]

The current-carrying capacity required of a ground wire is determined by the maximum current which the ground connection will be obliged to pass in the event of an accident to insulation, which in turn is determined by the rating of the nearest cut-out which will operate to break the circuit. The ground wire should under no circumstances be too small to carry this rated current safely. For lines, therefore, the ground wire will in most cases be of the same size as the line wire to which it is attached, but not in every case, because the line may be overhead and the ground wire inclosed for a considerable distance in wooden molding, and under such circumstances the ground wire would have to be larger than the line wire in order to provide a safe current rating. A contingency of this kind, of course, may arise infrequently, or not at all, but is cited here to emphasize the fact that the size of the ground wire should be determined by the rating of the nearest cut-out if it is greater than the safe current for the minimum size wire as set forth above. On the other hand, if it is smaller it has no effect on the size of the ground wire. It may be added that the foregoing remarks concerning ground wires for lines apply with equal force to ground wires for the noncurrent-carrying parts of electrical equipment.

The path of the ground wire should be as far as possible out of reach of persons, for it is to be considered dangerous, and as much care must be taken to make it inaccessible as would ordinarily be taken with a low-voltage line wire.[41] Where practicable this can best be effected by bringing it to ground from a point directly above the place where the electrode is buried. The portion accessible from the ground can then be guarded, both against mechanical injury and contact by persons. For this purpose it is preferable in every case to use guards of insulating material. Mechanical injury can, of course, be prevented by inclosing the wire in iron pipe or conduit, but the presence of the iron is objectionable because it acts as a choke coil and prevents free passage of alternating or oscillating currents, particularly those due to lightning, unless the wire is connected to the conduit at both

[40] See rule 93*b*, Appendix I.

[41] See Rule 93*c*, Appendix II.

ends. The latter does away with the choking effect, but introduces a second difficulty in that the conduit takes the potential of the ground wire in the event of current flow, and therefore may be dangerous. Hence, it seems that guards of insulating material are in every way preferable. Wooden molding serves the purpose very well and probably is as fully suited to it as anything. It is not intended, however, to convey the idea that there are no instances wherein iron conduit may not be used. On the contrary, such instances frequently arise, particularly in earthing frames of direct-current machines to water pipes, and in other cases. In fact, it may be stated that if the resistance of the earth connection is very low, and there is slight chance of the passage of alternating or oscillating currents, iron pipe or conduit may safely be used for mechanical protection, although it should be remembered that the best degree of electrical protection for persons is not at the same time secured.

VI. INSPECTION AND TESTING

1. INSPECTION

To obtain continuous and reliable service from ground connections good mechanical construction must be supplemented by adequate inspection.[42] The protection which the ground connection affords life and property may be destroyed by mechanical injury or corrosion, and it is therefore absolutely essential to safety that any defects found be remedied at the earliest practicable moment. That inspection has in many cases in the past been inadequate is shown by the correspondence with electric companies previously mentioned. Of the 418 companies from which replies were received, 132 reported as inspecting at intervals ranging from six months or less to five years, 59 reported no systematic inspection, 12 no inspection whatever, while 215 made no answer to the question regarding inspection. Of the entire number, 260 stated that they grounded low-voltage alternating-current circuits, and since only 191 reported inspection, it appears that something like 69 do no inspecting at all. Moreover, many of the 191 inspect so irregularly that the results are of little value. Of the 132 making regular inspection, however, 81 stated that they inspected at intervals of one year. This is a more or less satisfactory interval, and if adhered to will lead to fair results,

[42] See Rule 96*b*, Appendix II.

for the reason that deterioration by corrosion is not likely to produce marked effects in a single year.

Nevertheless, on account of the possibility of mechanical injury a shorter interval than one year is desirable. Under favorable circumstances inspection can be accomplished at intervals of much less than a year in such a way that no appreciable increase of expense is incurred. For example, meter readers may be instructed to look for broken earth wires when making their rounds, if the wires are conveniently located; or consumers may be impressed with the importance and necessity of keeping the ground connection in good condition and be requested to report faults to the electric company. Other expedients may suggest themselves in individual cases. In no case, however, should inspection at intervals not exceeding a year be omitted on the score of expense or for any other reason, for it is unsafe to leave a ground connection without attention longer than this.

2. TESTING

As stated before, it is always desirable, and in many cases very necessary, to learn as much as practicable of the electrical characteristics of a ground connection before it is put in service. Chief among these characteristics may be named resistance, capacity to dissipate energy, and possible potential gradient in the vicinity. In general, the first is the most important. The second may be important, but only in special cases. For if a ground connection complies with the safety requirements in regard to resistance and permanence it is not likely to fall short in regard to capacity to dissipate energy. Moreover, the first is easy to test for, whereas tests for the second not only take considerable time, but may also consume a large amount of energy. Tests for the potential gradient on the other hand are not particularly tedious nor expensive, but in the majority of cases the results will not justify the outlay if, as just stated, the safety requirements in regard to resistance are complied with. Hence, in preparing a ground connection for service, consideration should be given to whether it is likely to carry a heavy current. If it is, and circumstances are such that a sufficiently low resistance is difficult to obtain, it may be well to test for the capacity to dissipate energy, and also, perhaps, for the possible potential gradient if there is any possibility of injury to persons or animals. These tests, however, scarcely need to be applied to ground connections other than those for electrical circuits, and then only to those for the largest and most

important circuits. On the other hand, for ground connections to noncurrent-carrying parts of electrical lines or equipment, and to circuits from which the total possible flow of current to earth does not exceed 40 or 50 amperes, a simple measurement of resistance may in all cases be considered sufficient.[43] But even this test is unnecessary in the case of connections to water pipes if there is assurance that the pipe is continuous electrically for a hundred feet or more from the point where the earth wire is attached. Where there are insulating joints, however, a measurement of resistance is advisable.

As just stated, a measurement of resistance, and in some cases a measurement of capacity to dissipate energy, and possible potential gradient, should be made upon a ground connection when it is installed. If the soil conditions are normal; that is, not extremely wet or dry or cold, the results will give a fair indication of its future behavior. Subsequent tests may be confined entirely to resistance measurements, the period elapsing between tests depending largely upon the character of the ground connection. For the fault most likely to be disclosed by resistance measurements is that of corrosion beneath the surface of the ground. And in the case of pipes this can readily be kept account of by regular inspection, but with plates, corrosion, either of the ground wire or the plate itself, is most likely to be disclosed only by tests. Hence, resistance measurements of plates should be made oftener than of pipes. Moreover, where salt is used it is desirable to know when its effects are wearing away, and this can be ascertained most easily by resistance measurements. Tests, therefore, should be made at shorter intervals than where salt is not used. As a working basis it will probably be found that for driven pipes resistance measurements once in four years will be sufficient, for plates two years, and for salted ground connections, especially those for important circuits, one year. Such resistance measurements, combined with inspection at intervals of a year or less, will in all probability scarcely ever fail to show when a ground connection needs repairs, and will enable keeping it at all times in good condition.

The indications of resistance measurements are especially valuable, for the experiments previously described show that progressive changes in the resistance of ground connections are not likely to occur except by corrosion which may sever the ground

[43] See rule 96*b*, Appendix II.

wire or destroy the electrode. When therefore an electrode is shown by inspection to be seriously corroded, or by test to have an increase in resistance to flow of current away from it that can not be accounted for by freezing, drying of the soil, or washing away of salt, it should be promptly repaired or renewed. Discussion of methods of measuring resistance follow:

(*a*) AMMETER-VOLTMETER METHOD USING THREE CURRENT TERMINALS.—The ammeter-voltmeter method using three current terminals is the most reliable of any for making resistance measurements, especially if alternating current is available. Connections for making measurements in this way are shown in Fig. 30. Here

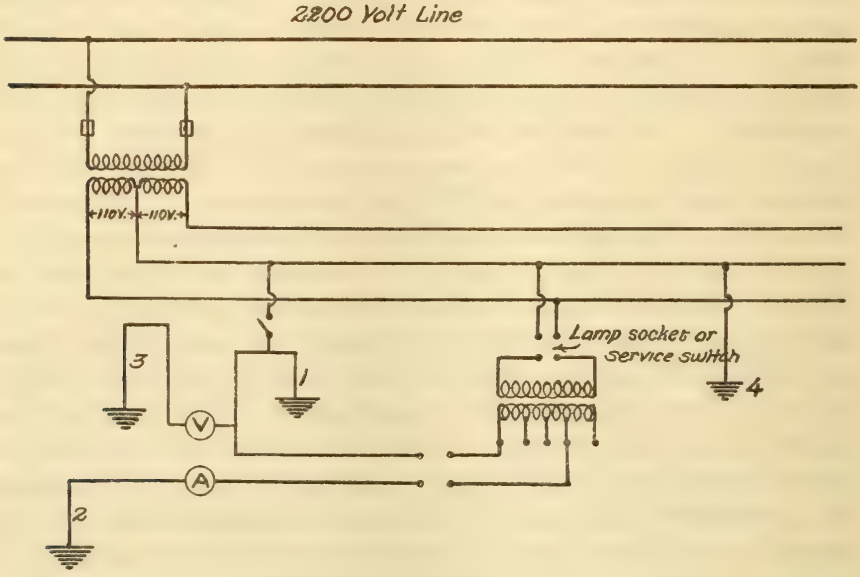

FIG. 30.—*Ammeter-voltmeter method using 3 current terminals*

a transformer having a 1 : 1, or any other suitable ratio, is connected to a low-voltage circuit through a lamp socket or a service switch. From the secondary of this transformer current is passed through each pair of ground connections; that is, 1–2, 2–3, 1–3, in series, the current and voltage in each case being read by means of the ammeter and voltmeter. From these readings the resistance between each pair of electrodes can be calculated. Let these resistances be designated by $r_{1\text{-}2}$, $r_{1\text{-}3}$, $r_{2\text{-}3}$, and the resistances of the individual specimens by R_1, R_2, R_3. From what has already been said on the subject of resistance of ground connections it is apparent that if 1, 2, and 3 are at some distance from each other the equations, $R_1+R_2=r_{1,\ 2}$, $R_2+R_3=r_{2,\ 3}$, and $R_1+R_3=r_{1,\ 3}$ are a fair approximation to the actual relationships existing

between these various quantities. Solving the foregoing equations it follows that $R_1 = \frac{r_{1,2} - r_{2,3} + r_{1,3}}{2}$, $R_2 = \frac{r_{1,2} + r_{2,3} - r_{1,3}}{2}$, and $R_3 = \frac{r_{2,3} - r_{1,2} + r_{1,3}}{2}$. Therefore, by measuring the resistance of each pair of electrodes in series, and substituting in these equations, results may be obtained which show very closely the actual resistance to flow of current away from each electrode. It is to be remembered, however, as mentioned above, that in every case the electrodes must be at some distance from each other, otherwise absurdities may arise in the calculations such as zero or even negative resistances.

To keep the required number of instruments at a minimum a transformer may be used, the secondary of which is wound for several voltages, such as 30, 60, 120, and 240. A single ammeter and usually but two voltmeters are then all that is necessary for measurements under ordinary conditions. Satisfactory results will be obtained in nearly all cases with an ammeter having a range of 2–10 amperes and one voltmeter reading say 80–300 volts and another 20–75 volts. To make such an outfit as portable as practicable the transformer should be small; its rating need not be greater than 0.5 kw. This size permits of connection to house lighting or power circuits and will give sufficiently large currents for accurate measurement upon any ground connection which is fit as far as resistance is concerned for grounding electrical circuits or equipment.

In Fig. 30 ground No. 1 is indicated as one of the ground connections of the low-voltage circuit. Before making the measurement the ground wire should be disconnected unless it is desired to measure the resistance of grounds 1 and 4 in parallel. Grounds Nos. 2 and 3 are of the nature of auxiliaries. These may be any piece of metal buried in the earth, such as a guy wire or a steel pole. The only conditions imposed upon these auxiliary grounds are that they be of sufficiently low resistance to give good current readings and sufficiently far apart, and from the ground connection being measured, not to interfere with the results. The greater this separation is the better, but for good results it should be at least 15 feet, although 6 feet need not be considered too small if circumstances are such that a saving of labor will result from using existing auxiliary grounds rather than making others more suitably located. At 15 feet, however, the mutual influence of the electric fields about two neighboring electrodes can be neglected as far as practical purposes are concerned.

The chief advantage of the method described above lies in the dependability of the results obtained. For, in the first place, a measuring circuit is provided which is cut off by insulation from all disturbing influences due to accidental or permanent grounds on the circuit from which energy is taken. Whereas, if the step-down transformer were not interposed between the low-voltage and the measuring circuits, and current were taken directly, a ground on the former would tend to give rise to stray currents through the ammeter that would cause errors to appear in the results. In the second place, on account of the comparatively high voltages and currents used, nothing in the way of stray currents of any kind in the earth is likely to disturb the measurements to an appreciable extent.

On the other hand, disadvantages are presented by this method in that even the lightest practicable outfit of transformers and instruments weighs so much that it is more or less inconvenient to transport; lamp sockets or service switches to which attachment may be made are not always within reach; considerable calculation is required before final results are obtained; and, if measurement is to be made upon an isolated ground connection, it may be necessary to make two auxiliary grounds. The last two disadvantages are mitigated somewhat by a modification of this method into what may be called the ammeter-voltmeter method using two current terminals.

(*b*) AMMETER-VOLTMETER METHOD USING TWO CURRENT TERMINALS.—The connections for this method are shown in Fig. 31. Here current is passed through two ground connections (1 and 2) in series, and the voltage measured between the one the resistance of which is to be found (1) and a third, or potential terminal (3). The resistance is then calculated simply by substituting in the equation $R=E/I$. Under favorable conditions good results may be obtained in this way. There is a source of error, however, which must be guarded against, and that is, if the resistance of the ground connection used as the potential terminal (No. 3) is sufficient to be comparable with that of the voltmeter a considerable discrepancy will be introduced into the calculated values, because the voltage reading will be proportionately less than the actual voltage; and, unless a correction is made, the resistance being measured will also appear to be less than it really is. Reasonable assurance must be had, therefore, that the resistance of the ground connection in series with the voltmeter is low enough

to avoid serious error. In the absence of such assurance, the resistance may be measured very simply and the corresponding correction made. There may, of course, be some question as to what constitutes a serious error, but it seems that in work such as this, where approximate results are all that are required, an error need not be considered serious unless it exceeds 10 per cent.

To determine whether the resistance of the third or potential terminal mentioned above can be neglected, use may be made of a voltmeter having two scales, on both of which the voltage can be read with a reasonable degree of accuracy. Then, with current

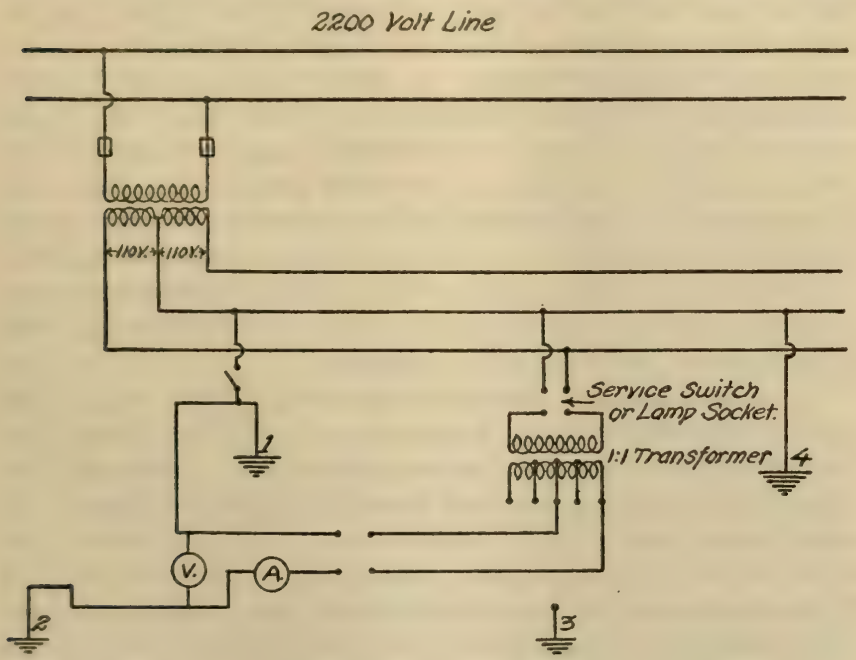

FIG. 31.—*Ammeter-voltmeter method using 2 current terminals*

flowing between the current terminals, take two readings between the potential terminal and either of the others, one on each scale of the voltmeter. If the readings are approximately the same numerically the resistance of the potential terminal can be neglected. On the other hand, if the reading on the low scale is considerably less than that on the high scale, the resistance of the potential terminal is high enough to introduce a considerable error.

The same results can be obtained by the use of a single scale voltmeter and a noninductive resistance equal in value to the resistance of the voltmeter. Take one reading with the volt-

meter alone; then place the resistance in series with it and take another. If the first reading is approximately double the second the resistance of the potential terminal may be neglected, while if the first is considerably less than double the second, a correction must be made.

This may be done as follows: Measure the total voltage and also take voltage readings between the potential terminal and each of the current terminals; then the total voltage is shared by the current terminals in proportion to the readings last mentioned. For example, if the current terminals are numbered 1 and 2, as in Fig. 31, and the total voltage is 110, while the voltage reading between the potential terminal and current terminal No. 1 is 40, and current terminal No. 2 is 30, current terminal No. 1 takes four-sevenths of the total voltage or 62.8 volts, while No. 2 takes three-sevenths or 47.2 volts. From the values so found and the current reading the resistance of either ground connection can be calculated by substituting in the equation $R=E/I$. Good results are obtainable in this way, and considerable labor is saved as compared with the method using three current terminals, because in this case the resistance of the potential terminal may be as much as half that of the voltmeter.

For very rough work the potential terminal may even be dispensed with entirely, and measurements made by passing current through two ground connections in series, measuring the total voltage and current, and assuming that the resistance of each ground connection is half the total. Here, however, the electrodes must be of the same size and shape, and be embedded in the same kind of soil to obtain results which are at all dependable.

(*c*) Ammeter-Voltmeter Method Using Direct Current.—It has previously been stated that alternating current is preferable for making measurements upon ground connections. There are places, however, where only direct current is available, and with it fair results may be obtained, but it is necessary to avoid sources of error which are negligible or do not exist where alternating current is taken from a special transformer. In the first place, the counter electromotive force of polarization is a considerable quantity with direct current, and to counteract it the applied voltage must be made large enough to make its effects of no consequence in comparison. For this 100 volts is sufficient, because the counterelectromotive force of polarization is not likely to be more than two or three volts, and hence, with 100 volts applied,

will not introduce an error of more than a few per cent. This means, of course, that 100 volts, or at least a large part of it, is actually to be applied to the ground connection under test, so when measurements are being made with direct current account must be taken of the fact that the total impressed voltage is shared by two ground connections in series, and if the resistance of the one under test is low, while that of the other is high, the division of voltage may be such that the effects of polarization introduces a considerable error. It is necessary, therefore, to see that the voltage is properly shared, which can be done only by making or choosing auxiliary ground connections of resistance equal to, or preferably less than, that of the one being tested. The best conditions as to division of voltage are obtained where a water pipe or a street-car rail is used for an auxiliary ground as is indicated below, since the resistance of the auxiliary here is very low. Under these conditions results practically as good as those from alternating current are obtainable, although direct current is not so convenient to work with.

In the second place, with direct current, care must be taken to ascertain whether there are ground connections on the circuit from which energy is being drawn other than those being investigated. If there are none the measurements may be allowed to go forward in the manner described above, using one or two auxiliary ground connections as the circumstances require, but if ground connections other than those being investigated do exist, and it is impracticable to disconnect them, this method must be discarded because of the errors introduced by cross currents. However, if the ground connections already existing are of sufficiently low resistance to serve as one of the auxiliaries, the test may be made by connecting the ground wire to one side or the other of the circuit, and measuring the current flow to ground, together with the voltage between the ground under test and an auxiliary ground connection near at hand, as shown in Fig. 32. The resistance is then computed from the equation $R=E/I$. The auxiliary ground in this case—that is, the potential terminal corresponding to ground No. 3 in Fig. 31—needs only to be of such a resistance as to be low in comparison with that of the voltmeter. The resistance of direct-current voltmeters being high, such an auxiliary ground is very easily constructed.

(*d*) KOHLRAUSCH-BRIDGE METHOD.—The apparatus and connections for this method are shown diagrammatically in Fig. 33.

The apparatus consists of a single dry cell in series with a buzzer and the primary coil of a small transformer. With the switch closed and the buzzer in operation, a pulsating current traverses the primary coil of the transformer, which in turn gives rise to an alternating current in the secondary. The secondary is connected to the current terminals of a wheatstone bridge, a telephone receiver being used in place of a galvanometer for the purpose of detecting when the bridge is in balance. The bridge should preferably be one of the easily portable ones commonly used for field work, such as a Leeds and Northrup type "S" testing set. The sensitiveness of the telephone receiver should

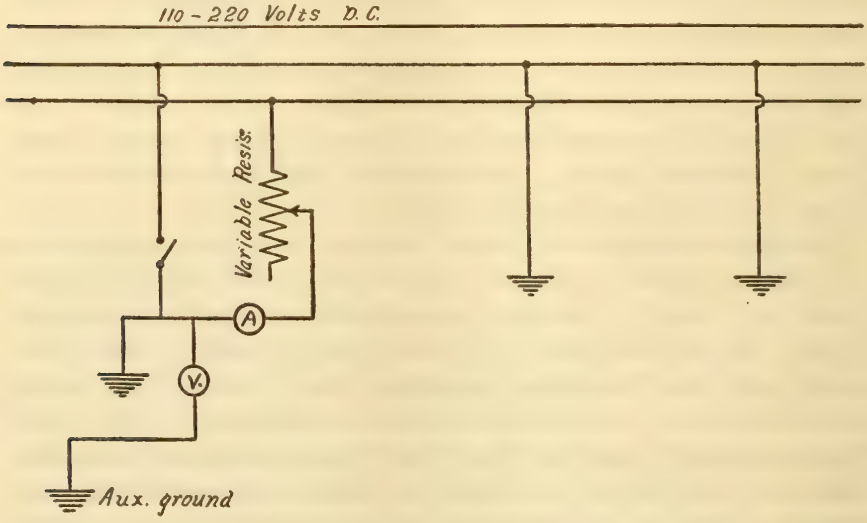

FIG. 32.—*Ammeter voltmeter method using direct current*

be rather low, because it is then less sensitive to the disturbing effects of stray current. The most suitable types of buzzer are those used in radio telegraph work, which can be made to give interruptions at a rate of several hundred per second. As to the transformer, a ratio of 1 : 10 does very well, although any other rates ranging, say, from 1 : 5 to 1 : 20, would serve. Its size is unimportant, except as far as portability is concerned. For this the lighter it is the better. There is no need of it weighing more than 2.5 pounds.

The method of procedure in making measurements is much the same as for the ammeter-voltmeter method; that is, with three ground connections at some distance from each other the resistance of each pair in series is measured and results substituted in

the equations given above. Or, if there are but two neighboring ground connections available, their resistances may be obtained by means of proportional resistances in much the same manner as in the ammeter-voltmeter method the resistances were obtained by means of proportional voltages. This method is described in detail in the next section. Finally, if there is a water pipe or a bonded rail near by, as in Fig. 33, either of these may be used as an auxiliary ground and its resistance neglected, thereby obtaining by a direct reading the resistance of the ground under test.

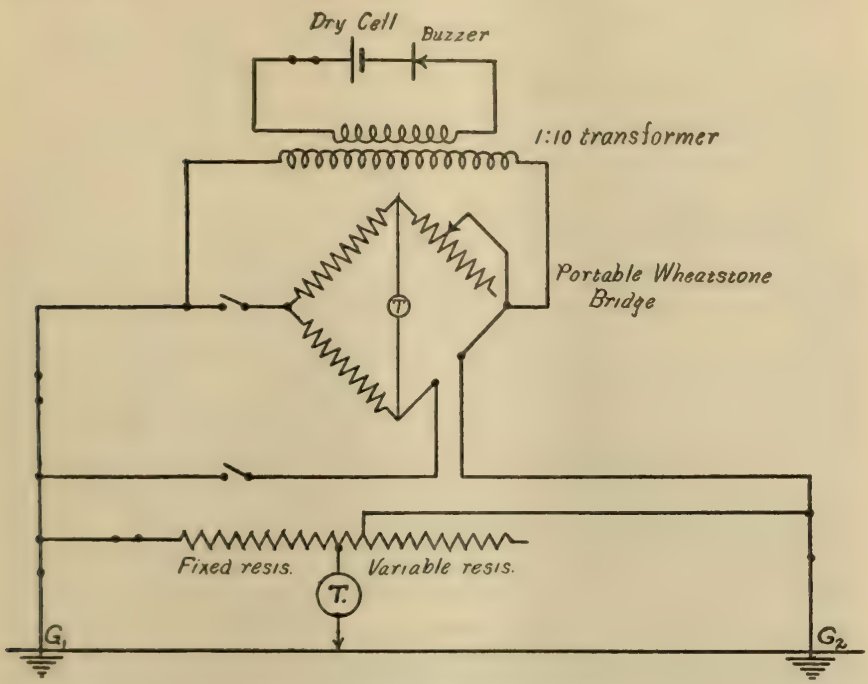

FIG. 33.—*Kohlrausch Bridge method*

The advantages of the bridge method of measuring the resistance of ground connections are as follows: In the first place, the results obtained are sufficiently accurate for practical purposes. Comparative measurements made at the Bureau of Standards show that this method and the ammeter-voltmeter method check within 2 or 3 per cent in nearly all cases, and in but few cases do errors arise which approach 10 per cent in value. In the second place, the source of energy constitutes a part of the apparatus itself, so it is not necessary to depend for measuring current upon the proximity of low-voltage circuits of any kind. In the third place, the outfit is easily portable and very rugged; and, in the

fourth place, a field experience extending over several months has disclosed but very few cases wherein for any cause the resistance of single ground connections that were disconnected from electrical circuits could not be measured. Lastly, direct readings are obtained, which do away with the need for computation.

The disadvantages of the method are not serious, but deserve some consideration here: First, the range of resistances which can be measured is limited, although it is greater than can be covered by the set of alternating-current ammeters and voltmeters heretofore described. The bridge gives good results from about 2 ohms to 200 ohms, and fair results from 200 ohms to about 3000 ohms. Below 2 ohms and above 3000 ohms it is not usually practicable to obtain measurements that are more than simply indicative of the order of magnitude of the resistance. It is very unusual, however, to encounter ground connections made with ordinary electrodes having a resistance of less than 2 ohms or more than 1000 ohms, so the inconvenience of the limits just mentioned is not great. Second, stray alternating, or even direct currents in the earth, on pipes or rails, or on the ground wire itself, may cause so much noise in the telephone receiver as entirely to obscure the sound of the bridge current, the sound produced by direct current arising from commutation, but it should be remarked here that if the ground connection being tested is disconnected from all electrical circuits the chances that stray currents will be sufficient to preclude the possibility of obtaining good results are small. Third, where an electrical circuit is grounded at several points it is practically impossible, except in rare instances, to measure the total resistance of all the ground connections in parallel with current on the circuit on account of the leakage to earth over the ground wires producing noises in the telephone receiver. Finally, if a ground connection is attached to an electrical circuit of considerable extent, or if a wire several hundred feet in length is necessary to reach the auxiliary ground, capacity and inductance effects may be such as to make it very difficult to detect the point of balance on the bridge.

The apparent reason for the failure of the bridge to operate satisfactorily outside of the limits named above is that with the arms adjusted to measure these high or low resistances the leading or lagging component of the current due to capacity or inductance in the leads produces much louder sounds in the telephone receiver than the component in phase with the impressed electro-

motive force, especially when the bridge is anywhere near a balance. The same effect is produced, with any adjustment of the arms of the bridge, if the ground being measured is connected to a circuit which is extensive enough to have an appreciable capacity between wires and earth. The result is that practically uniform sound is produced in the telephone receiver with successive settings of the dials, instead of a gradual decrease of sound as the point of balance is approached. There seems to be no feasible remedy for these effects. They could, of course, be eliminated, or at least greatly reduced, but the necessary apparatus would be too cumbersome, and the labor of making the adjustments too great, to be of any considerable assistance in the field, particularly as a real necessity for their elimination arises only infrequently. The effects of stray current may be overcome to a certain extent by making use of a telephone receiver of low sensitivity, and still further by means of a buzzer having a note much different from that of the stray currents. Leakage from circuits to ground need cause concern only where it is out of the question to cut the ground wire and splice it after the measurement is made.

It appears, therefore, that in practice the bridge method of measurement can be depended upon for reliable results in nearly all cases that are likely to arise. As stated above, it is hardly ever possible to obtain good results where the total resistance to ground of a live multiple-grounded circuit is desired, but this can be overcome by taking the grounds separately and calculating their combined resistance by means of the formula for the resistance of conductors in parallel.

(*e*) Modification of Kohlrausch-Bridge Method.—Where water pipes or rails are not available, and it is necessary to use auxiliary grounds, the resistance of which can not be neglected, application may be made of a modification of the method just described, which involves fewer measurements and less computation than the regular method, and also requires only one auxiliary ground instead of two. The procedure here is as follows: First, measure the resistance of the two ground connections in series, using the regular Kohlrausch bridge. Then connect in series between the two electrodes a fixed resistance and a variable resistance of several hundred ohms each, as shown in Fig. 34. From the point where these resistances are joined together connect a telephone receiver to ground by means of a short iron rod which can be thrust into the soil. Pass alternating or oscillating

current from the bridge set through the ground connections in series and adjust the variable resistance until minimum sound is produced in the telephone receiver. The total resistance to flow of current from one electrode to the other is shared by the electrodes in proportion to the fixed and variable resistances when adjustment is obtained. Thus if the total resistance were 30 ohms, and the resistances connected between the electrodes showed for minimum sound in the receiver 300 ohms and 200 ohms, respectively, one of the electrodes would have a resistance of three-fifths of the total, or 18 ohms, while the other would have a resistance of two-fifths of the total, or 12 ohms.

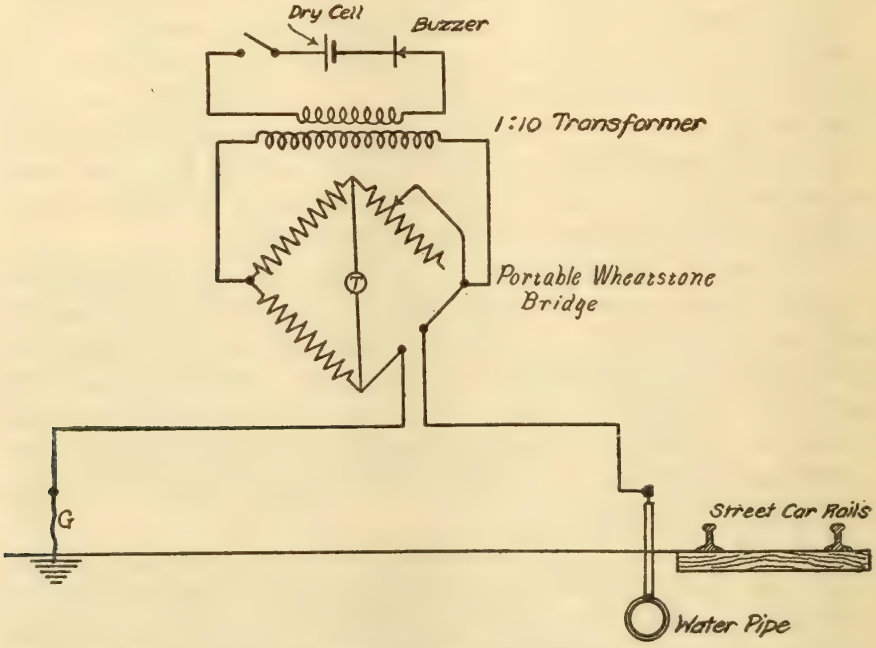

FIG. 34.—*Modified Kohlrausch bridge method*

The iron rod should be put down midway between the electrodes, or, preferably, at a considerable distance away from either of them at one side. Then, if there is a great difference in the resistances an error is not so likely to arise from being to one side or the other of the line of zero potential. The resistances for making the last measurement are readily furnished by the testing set mentioned above, that is, one of the fixed arms and the variable arm can be connected to the electrodes, the telephone receiver being put between the point where they are joined together and the ground.

The same troubles will be experienced in using this modified method as in the regular method, that is, disturbances will arise from stray currents, and difficulty will be encountered in obtaining a balance because of inductive effects due to long lead wires. Nevertheless, it is possible to obtain results in nearly all cases which are correct to well within 10 per cent. The method has been tried at the Bureau of Standards and found to be more or less satisfactory. It may be well to note here in passing that while more inconvenient than the bridge method, the ammeter-voltmeter method gives more consistent and reliable results than any other, and for that reason is preferable to any other for laboratory work, but for field work, where a certain amount of accuracy may be sacrificed to speed and convenience, the bridge method may be considered equal with, if not preferable to, the more laborious ammeter-voltmeter method.

(*f*) Testing by Lamp Banks, Fuses, and Magnetos.—At present many electric companies confine their testing operations to one or the other of the following methods: First, testing with lamp bank. This consists simply in connecting a lamp bank between one wire of the grounded circuit and the ground connection. Then, with the opposite side of the circuit grounded to a water pipe, a street-car rail, or other auxiliary ground connection that is supposed to be of fairly low resistance, current will flow through the lamp bank, and if this flow is sufficient to cause the lamps to light the resistance of the ground connection is considered low enough to give satisfactory service. Second, a two or three ampere fuse is sometimes used in place of the lamp bank. If the fuse is blown the conductance of the ground connection is taken as being suitable. Third, tests are sometimes made by means of a magneto. All that is considered necessary is that the resistance of the ground connection shall be such as to appear to short circuit the magneto when placed across the armature terminals in series with an auxiliary ground connection of some kind.

There are objections to all of these methods, for it is obvious that none of them gives even approximate information as to the resistance of the ground connection being tested, nor do they give any distinction as to different resistances for different purposes, since the same criterion is applied indiscriminately to earth connections for circuits of all capacities. It is true, of course, that blowing fuses and lighting lamp banks indicate that the resistance is within a certain maximum, but beyond this no informa-

tion is given. As for the test with a magneto it may be said that it gives no information at all, for if a magneto has an internal resistance of 600 ohms it would appear to be practically as thoroughly short circuited by 50 ohms as by 5 ohms, if the only means used for the detection of a completed circuit were the force required to keep up the speed, or the ringing of a bell, both of which are commonly resorted to where magnetos are much used in searching for accidental grounds.

It seems, therefore, that with the exception of rare cases these methods of testing ground connections should be discarded in favor of some more reliable method. The lamp-bank or fuse method may serve very well in testing for a broken ground wire, or for some similar purpose, but is of no use where it is necessary to know approximately the actual resistance of a ground connection. The magneto method should be abandoned altogether. Mere inspection is likely to tell as much of the resistance of a ground connection as this method of investigation. The chief disadvantage of the ammeter-voltmeter method or the bridge method, as compared with the less desirable methods described above, is, of course, the cost of the original outfit, but the increase in the value of the information obtained is well worth the outlay.

(*g*) SINGLE VOLTMETER METHOD.—Mention should be made here of another method which, as some times applied, is also very unreliable. In this a voltmeter is first connected across the line as shown at A in Fig. 35. The middle wire of the secondary circuit is then grounded at G_2 to the most convenient piece of buried metal within reach, and the voltmeter transferred to position B. The grounds G_1 and G_2 are then in series with the voltmeter, and the voltmeter reading at B is less than at A in proportion to the increase in resistance in the voltmeter circuit. If the reading at B is approximately the same as at A, the resistance of ground G_1 is considered low enough, whereas if the reading at B is a few per cent less than at A the resistance of ground G_1 is considered too high. It is obvious that the degree of accuracy obtained depends largely upon the resistance of the voltmeter. If this resistance is 3000 ohms, a change of 1 per cent in the reading between positions A and B would mean that the sum of the resistances of G_1 and G_2 in series was 30.30 ohms. A change of 2 per cent would mean 61.2 ohms and so on. To read accurately such small changes in deflection is, however, very difficult, and if there are fluctuations of voltage on the line it may appear that G_1 and G_2 have negative resistances, as would be the case if a

voltage rise should occur while changing from *A* to *B*. This could be overcome by using two voltmeters and taking simultaneous readings, but even in this way to tell the resistance of a ground connection within 50 or 100 per cent is out of the question unless a voltmeter of very low resistance is used.

(*h*) CAPACITY TO DISSIPATE ENERGY.—To test for the capacity of a ground connection to dissipate energy requires an auxiliary ground connection which can carry a greater current without a material increase of resistance than the one being investigated. Otherwise, the auxiliary ground will fail, and all the knowledge that is gained will be comprised in the fact that the ground con-

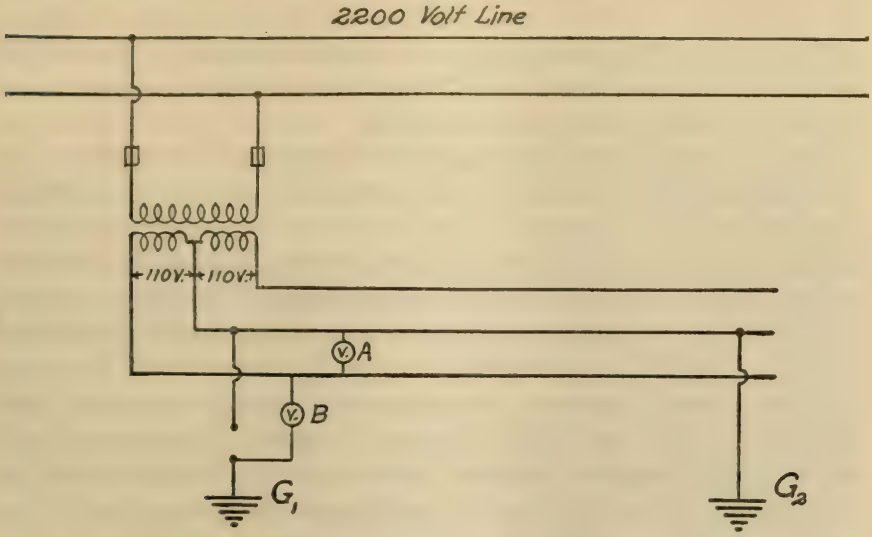

FIG. 35.—*Single voltameter method*

nection under test can dissipate energy at a higher rate than the other. In few cases, therefore, will it be found practicable to carry out satisfactory experiments unless the trouble and expense is incurred of making very elaborate auxiliaries. This difficulty does not arise, of course, where the ground connection to be investigated consists of several electrodes in parallel, for it may in such cases be possible to take each electrode separately, using the remaining ones as auxiliaries, and assuming that the total capacity to dissipate energy is equal to the sum of the individual capacities. Nor does it arise where there are water pipes within reach, although ordinarily under such circumstances the water pipes themselves should be used for grounding, which does away with the necessity for tests, but to investigate a single isolated

electrode requires the installation of a second ground connection of even greater conductance than the first. Local conditions will determine to a large extent the exact manner in which a test may best be conducted.

If power is supplied from transformers the capacity should, for the best work, be sufficient to run the rate of consumption of energy up to about 100 kw at 1100 volts. A larger power rating than this will hardly be required in any case, and in many, in fact, a smaller rating will do very well. Means should be provided for varying the voltage through rather a wide range, such as a water rheostat in the primary circuit. The current should be measured and also the voltage between the ground connection under test and a reference electrode embedded in the ground at some distance away. For these measurements current and potential transformers will be needed.

The first step in the experiment is to estimate the current which the ground connection will safely carry, and regulate the voltage accordingly. At the end of half an hour or so, if the current flow has not changed, it should be increased. Successive increases of current should be made at intervals until steam begins to come off. On the other hand, if the current at first is too large, and steam comes off very shortly, it must be decreased. In either case the current must be reduced until steaming ceases and then allowed to flow for several hours. If there is no appreciable increase of resistance the value of the current flow at the end of that time may be taken as the maximum which the ground connection will carry without excessive drying of the soil. But if an increase of resistance does occur, the current should be still further reduced until the resistance remains constant or nearly so. From the current and voltage the rate of dissipation of energy can be calculated, the voltage, as stated above, being that measured between the electrode under test and a reference electrode embedded in the ground at a distance of 15 feet or more.

(*i*) Potential Gradient.—Where it is desired to measure the potential gradient it is only necessary to pass current through the ground connection by means of an auxiliary ground and measure potential differences, either between points on the ground or between the electrode and points on the ground, depending upon the character of the electrode and the data required. For measuring potential differences a high-resistance voltmeter is preferable. Contact with the earth can be made by means of a small plate which can be pressed into wet soil, or a bar or pipe which can be

driven to a depth of 1 foot or so. The most important matter to be observed is one already mentioned, viz, that the resistance of the earth contact in series with the voltmeter be not so large as seriously to interfere with the readings. Furthermore, the voltage actually impressed upon the electrode under test must be great enough to give good readings on the voltmeter. This may require an auxiliary ground of rather low resistance in order that the voltage shall be properly shared, but it is essential to good results. Finally, if the current is sufficient to cause heating it should be left on only while readings are being taken, and discontinued while the earth contact is being moved from place to place.

(*j*) Low Voltage v. High Voltage in Testing.—In testing ground connections it sometimes appears that their resistance is an erratic thing which it is impossible definitely to ascertain. The experience of a number of persons has led them to believe that if a low voltage is impressed one value of resistance will be obtained, whereas if a high voltage is impressed the resistance will turn out to be something altogether different. From this it has been concluded that some kind of contact resistance exists between the metal of the electrode and the surrounding soil which requires a high voltage to overcome it before current can flow freely from the metal into the earth. That such a conclusion should be reached is not strange, but that the premises upon which it is based are not correct is shown by the discussion in regard to contact resistance given in the first part of Section II on the resistance of ground connections, and also by the measurements recorded in Table 12.

TABLE 12.—Comparative Measurements of Resistance

Ground No.	Ammeter-voltmeter method						Bridge method
	Voltage	Resistance	Voltage	Resistance	Voltage	Resistance	Resistance
		Ohms		Ohms		Ohms	Ohms
1–5	118	29.1	232	30.7	1130	28.4	.....
2–5	118	28.0	232	27.6	1120	27.0	.....
3–5	118	32.1	233	31.9	1130	31.2	.....
4–1	116	20.0	234	18.7	1080	18.4	.....
5–4	118	24.3	231	23.8	1095	23.8	.....
6	66.5	15.3	.....	.....	.....	.....	17.0
7	75.0	33.3	.....	.....	.....	.....	32.0
8	77.0	33.4	.....	.....	.....	.....	32.5
9	115.0	377.0	.....	.....	.....	.....	380.0
10	85.0	42.5	.....	.....	.....	.....	41.0

These measurements were made on driven pipes, all of which were 10 feet in length with the exception of No. 9, which was 1 foot in length. Numbers 1 to 5 were the same specimens as are enumerated in Tables 10 and 11, and were driven in filled ground containing a great deal of refuse. The rest were driven in clay and stones. The resistances given for Nos. 1 to 5 are for different pairs of driven pipes in series; that is, for 1 and 5, 2 and 5, and so on. In obtaining those for Nos. 6 to 10, the water-pipe system was employed as an auxiliary ground. Where the higher voltages were used the current was allowed to flow only while readings were being made in order to avoid heating the soil surrounding the pipes and thus changing the resistance. Nevertheless, slight changes did occur, especially at the higher voltages where readings were repeated to check for errors.

Now, none of the results given in Table 12 show discrepancies that can not be attributed to errors in measurement, or to fluctuations due to heating of the soil. Particular attention is directed toward the concordance between results obtained by the ammeter-voltmeter method and the bridge method. It appears fair to conclude, therefore, that in measuring the resistance of ground connections using alternating current the voltage makes little, if any, difference in the results.

The only way in which differences may be expected to arise is by the liberation of energy near the electrode in the form of heat if the current is allowed to flow for a considerable time. Here, if the voltage is low the rate of liberation of energy will be low, whereas if the voltage is high the rate of liberation of energy will also be high, with correspondingly greater heating of the soil. This at first causes a decrease of resistance which may amount to as much as 15 or 20 per cent, and if the rate of liberation of energy does not exceed a critical value previously discussed under the subject of dissipation of energy by ground connections, this decrease will remain in existence so long as current flows, but if the rate of liberation of energy does pass this critical value the soil will commence to dry out and an increase of resistance will follow. Hence, in making measurements of the resistance of ground connections, especially at high voltages, readings should be made immediately after the circuit is closed to avoid fluctuations of this kind. It may in some cases, of course, be desired to ascertain the fluctuations caused by heating at certain voltages, but not ordinarily, because the protective value of a ground

immediately following a failure of insulation or an accidental contact between wires depends in most cases upon the quick operating of fuses or circuit breakers, and this in turn depends upon the initial resistance.

Turning now to some of the causes for the conclusion mentioned above, viz, that the resistance of a ground connection depends upon the voltage applied, they may be summed up somewhat as follows: In the first place, where driven pipes are used it is not uncommon to find a coupling near the surface of the ground. In some cases a rather large pipe is driven in the ground, a reducer screwed on, and a small pipe taken a short distance up the pole for the purpose of placing the joint between wire and pipe out of reach of harm. The resistance of these screw joints has been found by measurement in several instances to be as much as 100 ohms. If an increasing voltage is applied to such a joint a point will be reached where the rust, red lead and oil, or other material which causes the high resistance will break down, with a sudden decrease of resistance, which may easily be taken as some phenomenon occurring in the ground connection itself rather than in the conductor leading to it. In the second place, in making tests, connection is sometimes made to fire plugs or service pipes that contain high resistance joints of the same kind as those described above, which, with a considerable voltage impressed will break down in the same way. In the third place, there is a tendency among some to reason that because in many cases when different voltages are applied to accidental grounds a decrease of resistance with increase of voltage occur, due to progressive breaking down of insulation, the same thing should occur with permanent grounds made by embedding an electrode in the soil.

But several things are here obvious: First, that the resistance of joints in pipes should in no way be considered as a part of the resistance of a ground connection. These joints should be looked upon rather as discontinuities in the ground wire or conductor and be treated as such. (See National Electrical Safety Code, rule 93, *a*.) Second, that permanent ground connections partake of very few of the characteristics of accidental grounds, and it is, therefore, a result of false reasoning to conclude that because in the one case it is not uncommonly found that a decrease of resistance occurs with an increase of voltage the same thing should be true in the other. Finally, that if the conductor leading to a ground connection is electrically continuous, it is of little moment

whether high or low voltage be employed in determining the initial resistance if the current is alternating.

(*k*) AUXILIARY GROUNDS FOR TESTING.—Where alternating current is used the making of auxiliary ground connections will not in many instances be found burdensome. When there are three or more houses or other buildings in a block in which there are lighting circuits, the ground connections already made can be utilized. If there are no existing ground connections within reach, two short pipes driven in the ground and well soaked with water will serve very well, and, if desirable, can be removed after the measurement is made. It is necessary only that sufficient current flow be obtained to give a fairly accurate reading of the

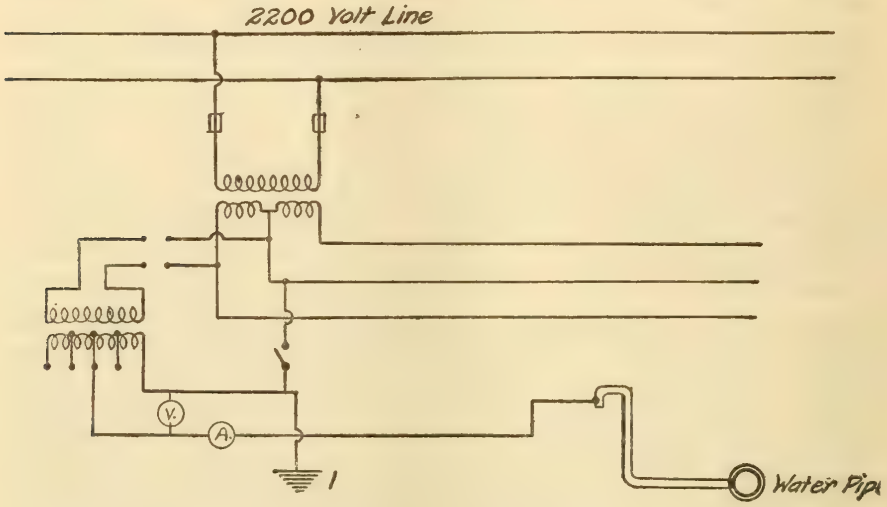

FIG. 36.—*Ammeter-voltmeter method using water pipe as an auxiliary ground*

ammeter. With direct current, however, it is best, as pointed out above, to make the resistance of the auxiliaries nearly equal to, or even less than, the resistance being measured in order to minimize the effects of polarization. The consequent difficulty in always securing suitable auxiliary ground connections constitutes a considerable disadvantage in the use of direct current for testing purposes.

It should be remarked in passing that the methods of making auxiliary grounds described in the preceding paragraph are intended to be applied only where a water pipe is not available. Where a driven pipe or plate is within reach of a water pipe, the task of making a measurement is much simplified. The resistances of nearly all water-pipe grounds are so low as to be negligible in

comparison with the resistance of driven pipes or plates, so all that is necessary to obtain a reasonably accurate measurement is to pass current through the ground to be measured and the water-pipe ground in series, as in Fig. 36, measure the total voltage, and substitute the results in the equation $R = E/I$, in the manner indicated above. Generally, no correction need be applied for the resistance of the water-pipe ground. In making such measurements, however, it is nearly always necessary to connect to the water pipe through a fire plug or a service pipe. These, in some instances, contain high resistance joints which may introduce errors, but they are not met with frequently enough to constitute a serious objection to the use of water pipes as auxiliaries. Moreover, where they are present, they usually give rise to results which are obviously in error and may be checked by means of another fire plug or service pipe. In the place of a water pipe, a bonded street-car rail may be used, since the resistance of ground connections made to these is in nearly all cases less than 1 ohm, although care must be exercised to see that stray railway currents through the ammeter are not sufficient to lead to serious discrepancies in the readings. A third means of establishing an auxiliary ground is by connecting to a grounded telephone messenger cable. The resistance to ground of these cables is usually somewhat higher than that of water pipes or bonded rails, especially bonded rails embedded in paving or soil, but they served very well where the others are out of reach.

(*l*) Leads, Clamps, and Other Accessories to Testing Outfits.—In addition to the transformers and measuring instruments previously mentioned, about 400 feet or more of single-conductor flexible cord, well insulated and mechanically protected, capable of carrying 10 amperes at least, and of known resistance per unit length, should be provided for the purpose of reaching such fire hydrants, service pipes, and other ground connections in the vicinity of the one being tested as will serve the purpose of auxiliaries. If the bridge method is employed, this cord should have a tap or pigtail every 50 feet for the purpose of making connection to binding posts, and be wound on a reel so it can be paid out or gathered in without tangling. The pigtails enable any desired length to be unreeled and be ready for use without disturbing the remainder where short distances are to be covered. It would be more convenient, of course, to bring the inner end of the wire out to a binding post and thus do away with the

necessity for pigtails, and this can be done where ammeters and voltmeters are used, but with the bridge to have a reel partly filled with wire in series with the ground connection disturbs the measurements on account of the inductance introduced. Aside from the cord just mentioned, the ammeter-voltmeter method requires in addition 100 feet of double-conductor flexible cord for

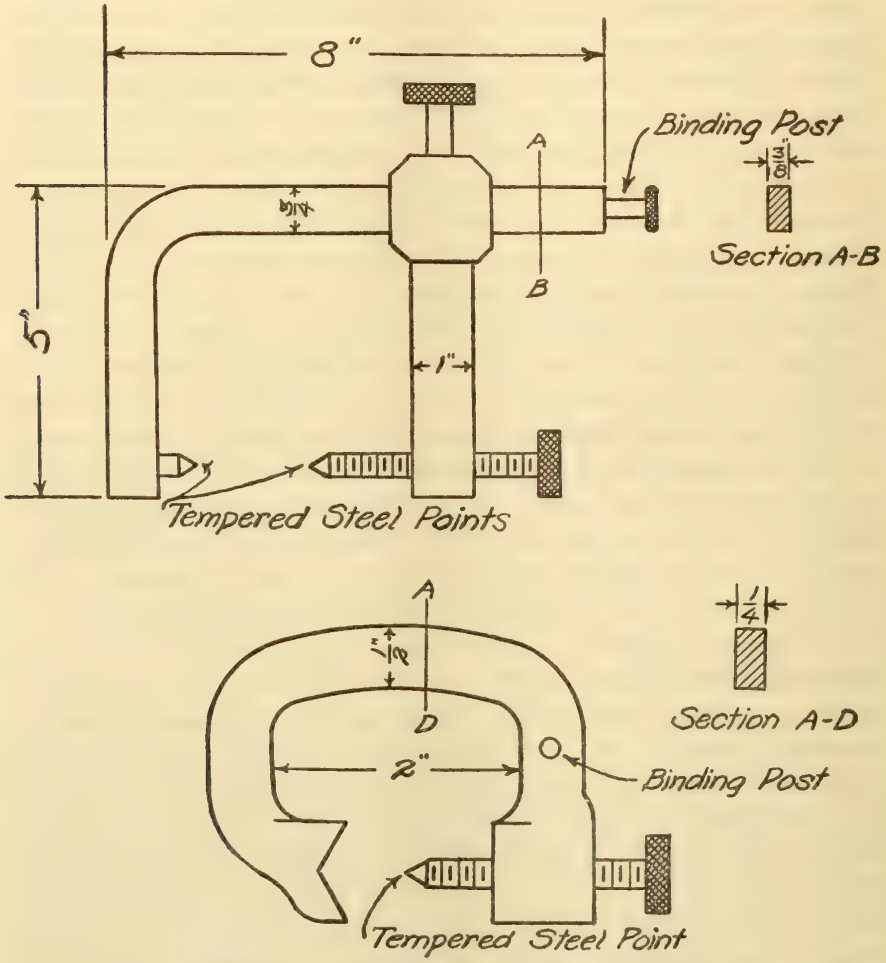

FIG. 37.—*Clamps for attaching to water pipes and ground wires*

reaching lamp sockets and service switches. These lengths will be found sufficient for nearly all cases that may arise.

For connecting wires to service pipes, fire plugs, and ground wires, two clamps are shown in Fig. 37. The larger one is designed for attaching to pipes and fire plugs, the sharp steel points being introduced for the purpose of piercing paint coatings and making

good contact with the metal. The smaller is intended for connecting to insulated ground wires. The sharp steel point easily penetrates through the insulation to the copper, and saves much time in many cases that would otherwise be consumed in skinning wires.

VII. FIRE HAZARD AND INTERFERENCE WITH SERVICE IN GROUNDING

The chief argument advanced against grounding in the past has been that it increases the fire hazard. In fact, it has been stated by many, largely on theoretical grounds, that the increase in the fire hazard is sufficient to outweigh any advantages that may follow from grounding, particular reference being had, of course, to the grounding of electrical circuits. Now such statements have at first sight an appearance of truth, for in a few cases where grounding has been resorted to as a protective measure fires have followed, but examination shows that by far the greater part of these fires have occurred in buildings where the wiring was in place for many years before grounding connections were made' and with old wiring there is undoubtedly some danger of fire unless care is taken to put the circuits in good condition before connecting them to earth. On the other hand grounding has undoubtedly averted many fires, both from high voltages on low-voltage circuits, and from leakage between accidentally grounded circuits or equipment and the earth, insufficient to blow fuses, but sufficient to cause arcing. Fires from new work, however, or even from old work which was not carelessly done in the first place, are of rare occurrence.

A second source of danger from fire or explosions is found where gas pipes are used for the purpose of grounding electrical systems. Several points concerning these two sources of danger and also the possibility that grounding may interfere with service are discussed briefly below.

1. WIRING

Where wiring which has been in place for a long time is grounded the chief difficulty encountered is that which arises from accidental grounds in buildings, trees, and other places. For a ground on one wire, which may have existed unnoticed, is likely soon to make itself apparent when another wire of the circuit is connected to earth. Current may then flow and cause fire, or at least loss of energy, unless steps are taken to ascertain the condi-

tion of the insulation and remedy any defects before damage occurs. Nevertheless, even with old work, fires do not occur with sufficient frequency to outweigh the beneficial effects, and it is likely that as many are averted as caused through the indication of accidental grounds by intentional grounding. This is shown to a considerable extent by the correspondence with electric companies previously mentioned, in which it was found that 14 companies out of 418 had experienced fires which they attributed to grounding, 182 made no statement in regard to fires, while 222 reported that no fires had occurred that could be traced to ground connections on their systems. Of the 14 companies reporting fires several had abandoned grounding entirely on account of them. Others stated that they had not commenced the practice of grounding because of doubt as to the real seriousness of the fire hazard. A large majority of the companies, however, seemed to be of the opinion that the fire hazard is negligible, and this opinion appears to be concurred in by a great many inspectors for insurance companies and others interested in the prevention of fires.

It must be admitted, however, that in earthing old work a certain amount of risk is incurred unless proper precautions are taken. In every case the insulation resistance between each wire and ground should be measured with a megger or by other means, and if the results show defects repairs should be made before the ground connection is attached. This, compared with fire losses, is a simple and relatively inexpensive procedure, and much to be preferred to earthing regardless of the condition of insulation and trusting to luck to escape the consequences of carelessness. It should be added that a circuit which shows defects by such a test constitutes a fire hazard whether grounded or not, and should be repaired.

On the other hand, with regard to the fire hazard in new work, or in old work which has been put in good condition, there is apparently no valid reason for believing that it is increased by connecting one of the circuit wires to ground. At least no reports are available which show an actual increase. Theoretically, wherever grounding necessitates increasing the strain on insulation to earth over what it would be with the circuit insulated, the fire hazard is increased because of the increased likelihood of failure of the insulation, but in low-voltage circuits this seems practically to amount to nothing. Whereas, even though there

were a large increase in the fire hazard from the low-voltage circuit, the reduction in the fire hazard from the high voltage would be more than ample to offset it. And since there is no tangible evidence that grounding does increase the fire hazard from the low-voltage circuit, the reduction in the fire hazard from high voltage appears to be all clear gain. Hence, as far as fire hazard is concerned, no good reason appears to exist for not grounding if the insulation of the low-voltage circuit is in good condition, rather there is an advantage from the standpoint of fire prevention as well as personal protection.

2. GAS PIPES

In grounding as it is practiced at present, considerable use is made of gas pipes. This is due in some cases to the fact that the electric companies own the gas systems. In others the use of the water pipes is forbidden, while that of the gas pipes is not. Now, there are several reasons why it is inadvisable to use gas pipes for making ground connections unless it be in special cases. In the first place, current flow in them is dangerous, for if a disconnection is made a spark may follow, and even a small spark may cause a fire or an explosion. In the second place, in laying them, cement or other insulating joints are used to a large extent, and the ground connection may, therefore, be poor and not of such a character as to give the required protection to life and property. And in the third place, where there are gas pipes there are in nearly all cases water pipes, making connection to the gas pipes unnecessary. In view of these facts connection to gas pipes should be avoided except in those cases where current flow through the ground connection is extremely unlikely to occur, or where other grounds are not available. Moreover, even in such cases care should be exercised to see that the pipe is electrically continuous for some distance into the ground and the ground connection of sufficiently low resistance to give the required protection. The cases in which grounding to gas pipes may be permissible include chiefly the noncurrent-carrying parts of small motors, electric-lighting fixtures, and other appliances in which, on account of fuses or other protective devices of low-current rating, a heavy flow of current to ground is practically impossible, and even a light flow unlikely, but for grounding electrical circuits the use of gas pipes should be prohibited.[44]

[44] See rule 94*a*, Appendix II.

On the other hand, it may perhaps be well to repeat at this point the statement that grounding to water pipes should not only be permitted, but be made compulsory, especially where safety to the public is involved. For it has been shown that such connection obviates both a life and a fire hazard that might otherwise arise when lightning or other cause destroys transformer insulation or wires become crossed. Inasmuch as it causes no appreciable disadvantage to either of the public-service companies concerned and both contribute to the life hazard by introducing pipes and circuits into buildings in many cases in close proximity to each other, there seems to be no good reason why city ordinances or other legislation to require it should be longer delayed. In numerous localities, the practice has been tried and found desirable, some statutes and ordinances have been passed requiring it, and it should be extended to all places where high-voltage alternating-current distribution systems are in use.

3. INTERFERENCE WITH SERVICE

In addition to the question of fire hazard, it has also been stated by some that grounding interferes with service; that is, in a circuit which is connected to earth a single accidental ground may cause a fuse to blow and interrupt the flow of current, whereas if the ground connection were omitted such an accidental ground might exist indefinitely without affecting the conditions of operation. This, of course, is true; but as in the case of fire hazard, experience has not shown that it is a factor that needs seriously to be reckoned with on account of the infrequency with which accidental grounds appear in low-voltage circuits except through careless work. Interference with service through accidental grounds on permanently grounded circuits may, therefore, be regarded rather as an argument against poor work than against grounding. Moreover, although it is true that a single accidental ground on a grounded circuit may lead to inconvenience, it is also true that where ground detectors are not used such a ground on a circuit which is not permanently grounded may exist *unnoticed* until a second ground occurs on the opposite wire, in which case the trouble would be no less than in the other, and might be worse, because by the time the fault made itself known there would be two accidental grounds of which either one or both might be in an inaccessible place. So for practical purposes the possibility of trouble from accidental grounds on grounded circuits can be considered as quite offset by the possibility of similar trouble arising with circuits which are not grounded.

VIII. COSTS

At the present time very little information is available in regard to the cost of making ground connections. This is due, in part at least, to the fact that many companies when grounding newly installed circuits include the outlay for the labor and materials required in the total cost of the installation. Others include it in maintenance, or under other heads, evidently considering the expense too small to justify the keeping of a separate account. In the correspondence with electric companies, previously referred to, a question was asked concerning the making of ground connections, and in reply 59 put the cost at from $1 to $2; 107, from $2 to $5; 23, from $5 to $10; and 5 at more than $10. Most of these figures, however, were specifically stated to be estimates. Moreover, there is no way of telling whether all of the charges which should have been included were taken into consideration. There is, therefore, some question as to the reliance which should be placed upon them. This doubt gains added force from the fact that other sources of information,[45] instead of putting the cost from $2 to $5, as did the majority of the replies quoted above, placed it from $6 to $15, which may or may not be higher than average costs. It should be added that 66 companies expressed themselves definitely to the effect that they grounded low-voltage alternating-current circuits, but made no mention as to their expenditures for grounding.

The chief causes for the foregoing great differences in cost lie, of course, in the character of the ground connection used, the kind of soil in which it is situated, the thoroughness with which the work is done, and also the items charged to the account of grounding. Where water pipes are used, the least expensive protection probably is obtained, although if a long run of wire is required, or much excavation, the cost may be as great as for other types. The connections which in general involve the smallest amount of labor and materials are those to service pipes. For these one company reports an average outlay of $2.05, this average being based on the installation of a large number at a time. Where only a few are to be made, however, the expense would be somewhat greater. One company stated that the cost ranged from $5 to $15, being somewhere near the lower figure where the circuit to be grounded enters the basement of a house, and somewhere near the higher figure where the circuit enters the attic,

[45] Electrical World, 49, p. 906; 55, p. 1012; 59, p. 1352; 59, p. 1215.

but it is likely that the higher figure would be found to apply only in extraordinary cases. For ground connections of other types the estimated cost ranges between as wide limits as for water pipes. In actual practice, however, the total cost may be expected to run uniformly higher. The increase amounts practically to that caused by the materials for the elctrode and the labor of embedding it in the ground. The only possibility of an offset to this increase lies in shortening the ground wire. That is, it often occurs that in making a connection to a service pipe a considerable distance has to be covered to reach the point of attachment to the circuit, whereas if a driven pipe or a plate is used it is nearly always practicable to locate it at a point which is much more convenient, and in that way a part of the expenditure of labor and materials which would otherwise be necessary in installing the ground wire may be saved. The saving in most cases, however, is too small to be of much moment.

With regard to maintenance the replies received were even more unsatisfactory than in respect to installation. Ten reported the average cost of maintenance as being from 10 to 25 cents per year; 17, from 25 cents to $1; 1, from $1 to $3; and 1, from $3 to $5. The rest, or 231 of the 260, stated that they grounded low-voltage alternating-current circuits, but had nothing to say as to maintenance.

It is practically impossible from these data to obtain more than a rough idea of the cost of making and maintaining ground connections. To make anything like a dependable statement requires that much more data be collected. Such data should cover the cost per unit length of running ground wires and protecting them from mechanical injury, of materials for electrodes and embedding them in different soils, and of making joints both to water pipes and to electrodes of other forms. With these points well covered a fairly accurate statement of cost could be made, which is very desirable where an entire system is to be grounded, or in any case where a considerable outlay for grounding is contemplated.

IX. BASES FOR SPECIFICATIONS

That the physical characteristics of ground connections should receive careful attention when specifications are written is evident from the foregoing discussion and experimental results, but particular instances of the lack of such attention in the past are found in many of the codes of rules concerning electrical construction

which are at present operative in the United States. In fact, the majority of these codes require no proof whatever of the fitness of a ground connection to serve the purpose for which it is installed. The tendency shown in their compilation has been to prescribe the form of ground connection to be used rather than the results that it shall be made to produce, which is the exact opposite of the tendency shown in many countries of Europe. The chief objections to an arbitrary ruling in this respect are based upon facts previously discussed in this paper, viz, that there is a great degree of variation in soil and moisture conditions from place to place, and also that there is a great degree of variation in the requirements placed upon ground connections for different purposes. As a consequence a form that will give satisfactory results in one place may give extremely unsatisfactory results in another place. Hence, in making specifications it is best to formulate the results which it is necessary to produce and leave the means to be used to be decided according to the facts and circumstances surrounding each case. This requires that the limiting values of at least the most important physical characteristics be designated.

Now, as already shown, in nearly all cases where ground connections are used their purpose is to prevent an unsafe rise of potential against ground of the system which they are intended to serve. This, in general, involves a flow of current of greater or less intensity, so resistance is the characteristic that must be given the greatest weight. That is, the degree of safety provided by a ground connection depends upon its resistance, which, unless conditions make it impracticable, must always be such that with the current flow to earth at the maximum value that it is likely to reach in the event of an accident to insulation, the potential difference temporarily existing between the grounded wire and any point on the ground shall not be high enough to be dangerous. Where persons may come in contact with circuits, or apparatus or appliances connected to them, this potential difference, for a good degree of safety, should certainly not much exceed 150 volts. On the other hand, where circuits and apparatus are inaccessible, and the chief danger presented is that to insulation between circuits and ground, higher voltages may be allowed. These, of course, are aside from the potential differences normally existing between the ungrounded wires of a circuit and ground due to the voltage of the circuit itself, which have little to do with

determining the resistance of the ground connection, the latter being determined almost entirely by the possible current flow in the ground wire and voltage rise between circuit and ground which may originate in accidental crosses or contacts with high-voltage lines.

As indicated above, many cases will be encountered where for a good degree of safety it will be necessary that the resistance be low enough to prevent the appearance of potential differences between grounded wire and ground from high-voltage lines exceeding 150 volts. It may happen, however, that soil conditions are so bad as to prevent obtaining a resistance which is sufficiently low for the purpose, or it may be that during certain seasons of the year drought or frost causes the resistance to reach very high values. Under such circumstances it will often be necessary to depend for safety partly or wholly upon other measures than grounding, or at least upon supplementary measures. An example of supplementary measures which may be resorted to is found in the isolation of fixtures and appliances, or in putting them where they can not be touched, except when the body is insulated from the ground. Another example is in the use of insulated coverings on the grounded circuit wires and even the ground wires themselves.

Another characteristic which should receive attention is capacity to dissipate energy. As to this there must be reasonable assurance that under normal conditions of moisture a ground connection will carry for a considerable period, without an increase of resistance, the maximum current that is likely to flow. Reasonable assurance, however, is about all that can be required in this respect. For, in the first place, so much depends upon the moisture content of the soil, and, in the second place, so much time and electrical energy must be expended in making tests that to specify rigorously the capacity of a ground connection to dissipate energy would in all but a few cases lead to greater expense than the results would justify. Attention to the extent of testing need be required only where the current flow may be of the order of hundreds of amperes, and where at the same time the resistance is not as low as it should be. In general, it may be stated that if the safety requirements in regard to resistance are complied with, especially safety to life, the capacity to dissipate energy may be taken as sufficient. Water-pipe grounds may be reckoned as almost universally satisfactory, but artificial grounds, unless in multiple, may in many cases be unsatisfactory.

Likewise, as far as potential gradient is concerned, if the resistance is sufficiently low for safety, there is slight danger to persons from potential differences in the ground. There is, however, a source of danger in potential differences between ground wire and ground, but to avert it all that is necessary is to cover the wire with insulating material as indicated previously in this paper. Animals, on the other hand, are very susceptible to electric shocks, and much trouble will be avoided if it is required that where there is a possibility of such trespassers coming near ground connections the immediate vicinity be made inaccessible to them by fencing or other means.

In conclusion, long life of the ground connection is very desirable and should be given special consideration in making specifications. To this end the construction should be made very substantial, as emphasized heretofore. The materials used should not present galvanic couples at joints, or, if they do, corrosion should be prevented by painting, coating with tar or pitch, or embedding in concrete. The means employed for reducing the normal resistance should not be extraordinarily detrimental to the electrode. Moreover, such means should be allowed only where adequate inspection and repairs are made; otherwise there is small assurance that salt, for instance, will be renewed when its effects wear away.

With these points well covered fair results may be expected, but at the same time it should be remarked that the available data upon which specifications may be founded are incomplete. Much more information is necessary before grounding, at least to artificial grounds, can be placed upon as sound a basis as is desirable. This information should comprise resistance, capacity to dissipate energy, variation of resistance with seasons, the period required for the effect of salt and other substances to wear away, the life of the electrodes, and costs, both of installation and maintenance, in soils of all kinds. Moreover, the performance of ground connections in service should be noted at every opportunity, and a record made of their electrical characteristics. In the course of time much valuable information could be accumulated in this way which would be of great assistance in safeguarding life and property from electrical dangers. To begin this task, the Bureau of Standards has recently sent a representative to cities in different sections of the country to measure the resistances of a large num-

ber of such artificial ground connections as are now used for protective purposes. The results of these measurements are tabulated and discussed below.

X. FIELD MEASUREMENTS OF THE RESISTANCE OF ARTIFICIAL GROUND CONNECTIONS

The results of field measurements made up to the present time are set forth in Table 13, which shows the cities visited, the types of grounds tested, the kind of soil in which the electrodes were embedded, the auxiliary grounds used, and, in the last column, the resistances. The cities named were selected mainly because it was known that in them driven pipes, plates, or grounds of forms other than water pipes were used either exclusively or to a considerable extent. In making the selection an attempt was also made to include points in some of the New England States, the Middle Western States, and the Rocky Mountain States.

TABLE 13.—Resistance of Ground Connections

NEWARK, N. J.

Ground No.	Type	Depth	Soil	Auxiliary ground	Resistance
		Feet			Ohms
1	1¼-inch driven pipe, 10 pounds salt.	6	Red clay	Water pipe	2.5
2	do	6	do	do	22
3	do	6	do	do	2
4	do	6	Red clay under building, dry.	do	800
5	do	6	Clay and loam in sump of garage.	do	7
6	do	6	Clay and loam wet with brine.	do	3.5
7	do	6	Clay, rather dry	do	42
8	do	6	Low, marshy	do	3
9	do	6	do	do	3

PATERSON, N. J.

1	Two 1¼-inch pipes driven 6 inches apart.	6	Stony clay and loam	Measured by 3-point method.	404
2	½-inch driven pipe in cellar	8	do	do	268
3	Driven well, size of pipe and depth not known.		Stony clay	do	20
4	Steel trolley poles set in concrete.	5	Sandy	Two poles in series	310
5	do	5	do	do	700

TABLE 13.—Resistance of Ground Connections—Continued

ELIZABETH, N. J.

Ground No.	Type	Depth	Soil	Auxiliary ground	Resistance
		Feet			Ohms
1	1¼-inch driven pipe, 10 pounds salt.	6.5	Shale	Water pipe	22
2	do	9	Red clay and shale	do	12
3	do	9	do	do	15
4	do	9	Red clay	do	19
5	do	10	Sand and gravel, dry	Bonded rail	190
6	do	10	Wet sand and gravel, marshy.	Water pipe	41
7	do	10	Red clay and gravel, dry.	Two pipes in series	160
8	do	7	Red clay, some gravel	Bonded rail	40
9	do	10	Red clay, beside ditch	do	4.5
10	do	10	do	Water pipe	8

NEW YORK CITY, BRONX DISTRICT

1	3-inch service stand pipe 35 feet long.	3	Ground low	Water pipe	6.5
2	do	3	do	do	6
3	do	3	Gravelly	Bonded rail	10
4	do	3	Stony, on hill	Water pipe	20
5	do	3	do	do	45

PROVIDENCE, R. I.

1	¾-inch driven pipe	10	Gravel and sand	Water pipe	260
2	do	10	Gravel and clay	Bonded rail	70
3	do	10	Gravel	Water pipe	2500
4	do	10	Gravel and sand	In series with a number of grounds at other points, 4 at least.	1700
5	do	10	Stones, gravel, sand	Measured by 3-point method.	2700
6	do	8	do	do	1300
7	Local water system, driven well, 100-foot pipe.		do	do	300
8	¾-inch driven pipe	10	Gravel and sand	Water pipe	700
9	do	10	do	do	250
10	do	10	do	do	800
11	do	10	3 feet loam over fine sand.	do	115
12	do	10	Gravel	do	630
13	do	10	do	do	1300
14	do	10	Sandy	do	800
15	do	10	Gravel	do	1100
16	do	10	do	Several other grounds on neutral.	370
17	do	10	do	Two grounds in series	1300
18	do	10	do	Other grounds on neutral	900
19	2-inch driven pipe, substation ground.	20	do	Water pipe	30
20	¾-inch driven pipe	10	Gravel and sand on hill.	Bonded rail	2700
21	do	10	Gravel and sand, stones.	Other grounds on neutral	1100

TABLE 13.—Resistance of Ground Connections—Continued

NEW HAVEN, CONN.

Ground No.	Type	Depth	Soil	Auxiliary ground	Resistance
		Feet			Ohms
1	Four ¾-inch pipes driven 18 inches apart.	8	Gravel and sand	Common ground wire	170
2	¾-inch driven pipe	6	Gravel and sand in damp cellar.	do	250
3	Local water system, 50-foot pipe.	3	Gravel and sand	do	40
4	Local water system, 100-foot pipe.	3	do	do	15
5	¾-inch driven pipe	8	do	do	920
6	do	8	Gravel, sand, clay	do	170
7	do	8	do	Bonded rail, also common ground wire.	85
8	do	8	Gravelly	Bonded rail	160

BOSTON, MASS.

1	1½-inch driven pipe, perforated, patented device.	6	Sandy dry	Neutral grounded at 3 other places.	700
2	2-inch driven pipe	10	do	In series with 50-foot service to cement water main.	1400
3	do	40	Swampy ground	Messenger of telephone cable.	25
4	Local water system, 700-foot pipe.	3	Gravelly	Bonded rail	14
5	1-inch driven pipe	6	Gravel and sand	do	880
6	Copper plate in cesspool	8	Gravel and sand over rock.	do	30
7	2-inch driven pipe	10	Gravel and sand	Measured by 3-point method.	950
8	Local water system, 100-foot pipe.	3	do	do	1150
9	Pole guy	5	do	do	2250
10	2-inch driven pipe	20	Sandy, moist, in draw	Water pipe	105
11	do	6.5	Gravelly, pipe driven to rock.	do	1100
12	do	4.5	Gravelly, dry around pipe.	do	2100
13	Three 2-inch pipes driven touching each other in wet manhole.	12	Gravel and clay	do	23
14	Three 2½-inch pipes driven touching each other in wet manhole.	10	do	do	19
15	2½-inch pipe in bottom of 8-foot manhole.	12	do	do	13
16	2½-inch pipe in bottom of 8-foot manhole, salted.	24	do	do	65
17	2-inch pipe in 6-foot manhole.	10	do	do	38
18	1-inch pipe in 6-foot manhole.	6	do	do	45
19	do	6	do	do	46
20	Plate 2 feet square	6	Low ground covered with stable refuse.	do	7

TABLE 13.—Resistance of Ground Connections—Continued

PHILADELPHIA, PA.

Ground No.	Type	Depth	Soil	Auxiliary ground	Resistance
		Feet			Ohms
1	2-inch driven pipe	8	Low ground	Water pipe	16
2	do	8	do	do	17
3	do	6	do	do	29
4	do	6	Low ground near Delaware River.	do	40
5	do	6	Low ground	do	23
6	do	6	do	do	16
7	do	8	do	do	21
8	do	5	Filled ground, cinders, slate.	3-point method	8
9	do	6	Low ground	Water pipe	23
10	do	6	do	do	21
11	do	6	do	do	32
12	do	6	do	do	28
13	do	6	do	do	26
14	do	6	do	do	12
15	do	6	do	do	17
16	do	6	Clay and stones, rather high.	do	180
17	do	6	Low ground	do	15
18	do	6	Clay	do	42
19	do	6	Clay and stones, high ground.	do	65
20	do	6	do	do	130
21	do	6	do	150-foot water service to cement main.	170
22	do	6	High stony ground	Water pipe	330
23	do	6	do	do	1400
24	do	6	High ground, clay and stones.	do	430
25	do	6	do	do	390
26	do	6	do	do	101
27	do	6	High and stony	do	210
29	do	6	do	do	105
30	do	6	do	do	165
31	do	6	do	do	115
32	do	6	do	Bonded rail	65
33	do	6	Clay, high	do	55
34	do	6	Clay and stones, high	do	450
35	do	6	do	do	380
36	do	6	Clay wet by waste water	Water pipe	13.5
37	do	6	Clay and gravel	Bonded rail	200
38	do	6	Clay, low	Water pipe	23
39	do	6	do	do	38
40	do	6	do	Bonded rail	27
41	do	6	Clay	Water pipe	75
42	do	6	Clay and sand	do	110

TABLE 13.—Resistance of Ground Connections—Continued

SCRANTON, PA.

Ground No.	Type	Depth	Soil	Auxiliary ground	Resistance
		Feet			Ohms
1	1-inch driven pipe	5	Clay and gravel	Water pipe	135
2	do	5	do	do	95
3	do	5	do	do	100
4	do	5	do	do	240
5	do	5	Gravelly	do	350
6	do	5	do	do	195
7	do	5	do	do	19
8	do	5	do	do	135
9	do	5	Gravelly, top of knoll	do	490
10	do	5	Gravelly, stony	do	40
11	do	5	do	do	95
12	do	5	do	do	100
13	do	5	do	do	71
14	do	5	do	do	155
15	do	5	do	do	155
16	do	5	do	do	85
17	do	5	do	do	300

OMAHA, NEBR.

1	Hydroground	6	Yellow clay	Water pipe	20
2	do	6	do	do	60
3	do	6	do	do	37
4	do	6	do	do	55
5	do	6	do	do	29
6	do	6	do	do	18
7	do	6	do	do	22
8	do	6	do	do	19
9	do	6	do	Bonded rail	10
10	do	6	do	Water pipe	35
11	do	6	do	do	19
12	do	6	do	do	25
13	do	6	do	Bonded rail	33
14	do	6	do	Water pipe	11
15	do	6	do	Bonded rail	35
16	do	6	do	do	27
17	Plate 18 by 24 inches in small amount of charcoal	6	do	Water pipe	30
18	do	6	do	do	28
19	do	6	do	do	29
20	1 inch driven pipe	10	do	do	6.5
21	Two 1-inch driven pipes 6 inches apart.	10	do	do	11.0
22	1-inch driven pipe	10	do	Bonded rail	12
23	do	6	do	do	35
24	do	10	Yellow clay, high, rather dry.	do	45
25	do	10	Yellow clay	do	14
26	do	10	Yellow clay, hollow, water settles.	do	6
27	do	10	Yellow clay	Water pipe	21

TABLE 13.—Resistance of Ground Connections—Continued

OMAHA, NEBR.—Continued

Ground No.	Type	Depth	Soil	Auxiliary ground	Resistance
		Feet			Ohms
28	1-inch driven pipe in parallel with steel pole.	10	Yellow clay	Bonded rail	14
29	do	10	do	do	5
30	1-inch driven pipe	10	Yellow clay, very wet, broken water main.	do	3.5
31	do	10	Yellow clay	do	4.5
32	do	10	do	Water pipe	7.0
33	do	10	do	do	9.0

DENVER, COLO.

1	1-inch driven pipe	8	Clay over sandy loam	Water pipe	25
2	Coil No. 4 wire at base of pole.	6	Clay	do	15
3	1-inch driven pipe	8	do	do	45
4	do	8	Loam over gravel	do	125
5	do	8	Coarse gravel	do	190
6	do	8	Sandy soil over gravel	do	48
7	do	8	Clay	do	17
8	do	8	Gumbo	do	7
9	do	8	Clay over sand	do	28
10	do	10	Sandy loam	do	15
11	do	8	Sandy loam and gumbo	do	45
12	do	8	Gravel and gumbo	do	18
13	do	8	Gravelly	do	55
14	do	8	do	do	72
15	do	8	Gumbo over gravel	do	52
16	Paragon cone	6	Gravelly	do	210

COLORADO SPRINGS, COLO.

1	1-inch driven pipe	8	Gravel	Water pipe	200
2	do	8	Sand and gravel	do	350
3	do	8	Adobe	do	90
4	do	8	do	do	16
5	1-inch driven pipe with arc light carbons around it.	8	Red sand	do	14
6	1-inch driven pipe	8	Adobe and gravel	do	85
7	do	8	Sand	do	63
8	do	8	do	do	35
9	do	8	Sandy	do	13
10	do	8	Adobe	do	55

PUEBLO, COLO.

1	¾-inch driven pipe	18	6 feet of dump over sand	6-inch driven well	4.5
2	do	18	do	do	3.5
3	do	6	Adobe and stones	Water pipe	210
4	do	8	Adobe with some gravel	do	35
5	do	12	do	do	46

TABLE 13.—Resiatance of Ground Connections—Continued

PUEBLO, COLO.—Continued

Ground No.	Type	Depth	Soil	Auxiliary ground	Resistance
		Feet			Ohms
6	Four ¾-inch pipes driven 6 feet apart.	12	Sandy	Water pIpe	15
7	¾-inch driven pipe	6	do	do	75
8	do	6	do	do	7
9	do	6	do	do	65
10	do	6	Filled ground	do	12
11	do	6	do	do	14
12	do	6	do	do	8
13	do	6	do	do	8
14	do	6	Adobe	do	13
15	do	6	do	do	33
16	do	8	do	do	18
17	do	8	Adobe wet from exhaust pipe.	do	14
18	do	8	Adobe	do	77
19	do	6	do	do	25
20	do	6	do	do	13
21	do	6	Sandy	do	26
22	do	6	do	do	60

LEADVILLE, COLO.

1	Coil No. 0 stranded wire in bushel of charcoal.	8	Stony, side hill	Water column in mine	200
2	do	8	Sandy, wet by waste from stamp mill.	Water pipe, running under stamp mill.	33
3	do	8	Stony, with sand and clay.	Water pipe	53
4	do	8	Stony, beside wet gutter	do	137
5	do	8	Stony, near old ash pile	do	25
6	¾-inch driven pipe	8	Stony	do	44
7	Coil No. 1 wire in charcoal.	8	do	do	28
8	¾-inch driven pipe	6	Stony, in ash pile	do	48
9	Coil No. 1 wire in coke	8	Stony	do	42

SALT LAKE CITY, UTAH

1	Two ¾-inch pipes driven 2 feet apart.	8	Black loam 5 feet deep over gravel, low.	Water pipe	5.5
2	do	8	do	do	13
3	¾-inch driven pipe	8	Black loam over gravel	do	15
4	do	6	Dry, stony soil, on bench	do	140
5	do	8	do	do	93
6	do	7	do	do	105
7	do	8	Sand, gravel, clay	do	18
8	do	7	Gravelly, on bench	do	210
9	do	8	Stony, on bench	do	86
10	do	8	do	do	115
11	do	7	Very stony, on bench	do	210
12	Two ¾-inch pipes, driven 3 feet apart.	8	Sandy, rather low	do	9

TABLE 13.—Resistance of Ground Connections—Continued

SALT LAKE, CITY, UTAH—Continued

Ground No.	Type	Depth	Soil	Auxiliary ground	Resistance
		Feet			Ohms
13	Two ¾-inch pipes, driven 18 inches apart.	8	Cinder dump, low ground	Water pipe	5.5
14	¾-inch driven pipe	8	Gumbo over sand	do	10.5
15	do	8	do	do	17
16	do	8	do	do	14
17	do	8	Adobe with some stones.	Bonded rail	18
18	do	8	Gravelly	Water pipe	25

BUTTE, MONT.

1	½-inch pipe driven in bottom of post hole.	4	Wash sand, decomposed granite.	Water pipe	380
2	Coil of No. 4 wire at foot of pole.	5	Wash gravel	do	240
3	do	5	Wash sand, decomposed granite.	do	145
4	¾-inch driven pipe	7	do	do	140
5	⅝ driven rod	7	do	do	140
6	do	7	do	do	160
7	Coil of No. 0 wire at foot of pole.	5	Clay	do	55
8	Coil of No. 4 wire at foot of pole.	5	Gravel and sand	do	65
9	do	5	Dump from mine	do	42
10	do	5	Dump; rock, cinders, sand	Bonded rail	33
11	do	5	Clay and stones	Water pipe	85
12	do	5	Decomposed granite and stones.	do	78
13	do	5	Filled ground	do	18
14	do	5	Decomposed granite, stones.	Bonded rail	111
15	do	5	Tailings from smelter, damp.	do	17
16	do	5	Sandy	Water pipe	140
17	do	5	Stony side hill	do	80
18	do	5	Silt and sand	Bonded rail	92
19	do	5	Sand and stones	Water pipe	57
20	do	5	Sandy	do	140
21	do	5	Decomposed granite	Bonded rail	140

HELENA, MONT.

1	1-inch driven pipe, about 3 pounds salt.	8	Decomposed limestone, stones.	Water pipe	36
2	do	6	do	do	205
3	do	8	do	do	48
4	do	8	do	do	65
5	do	8	do	do	155
6	do	8	Stony	do	105

TABLE 13.—Resiatance of Ground Connections—Continued

HELENA, MONT.—Continued

Ground No.	Type	Depth	Soil	Auxiliary ground	Resistance
		Feet			Ohms
7	1-inch driven pipe, about 3 pounds salt.	8	Decomposed limestone, stones.	Water pipe	38
8	do	8	do	do	55
9	do	8	do	do	50
10	do	8	do	do	88
11	do	8	Clay and stones	do	21
12	do	8	do	do	45
13	do	8	do	do	34
14	do	7	do	do	160
15	Two 1-inch driven pipes, about 3 pounds salt.	8	do	Bonded rail	45

MOORHEAD, MINN.

1	¾-inch driven pipe	7	Black loam over clay	Water pipe	7
2	do	7	do	do	35
3	do	7	do	do	19
4	do	7	do	do	14
5	Paragon cone	6	do	do	21
6	½-inch driven pipe	7	do	do	90
7	Paragon cone	6	do	do	45
8	¾-inch driven pipe	7	do	do	11
9	do	7	do	do	50
10	1-inch driven pipe	7	do	Bonded rail	13
11	½-inch driven pipe	7	do	do	55
12	Paragon cone	6	do	Water pipe	11

MINNEAPOLIS, MINN.

1	1-inch driven pipe	7	Gravelly	Water pipe	46
2	¾-inch driven pipe	10	do	do	240
3	do	8	do	do	27
4	do	7	do	do	210
5	do	8	do	do	490
6	do	8	do	do	320
7	1-inch driven pipe	8	do	do	59
8	¾-inch driven pipe	8	Gravel, clay, sand	do	260
9	do	8	Filled ground	do	28
10	Two 1-inch driven pipes near each other.	8	Gravel	do	155
11	1-inch driven pipe	8	Clay and stones	do	57
12	do	8	Black loam over sandstone.	do	16
13	¾-inch driven pipe	8	Stony	do	340
14	1-inch driven pipe	8	do	do	80
15	¾-inch driven pipe	8	Clay	do	98
16	do	8	do	do	72
17	do	8	do	do	32
18	do	8	Gravelly	do	105
19	do	8	Filled ground	do	7

TABLE 13.—Resistance of Ground Connections—Continued

MINNEAPOLIS, MINN.—Continued

Ground No.	Type	Depth	Soil	Auxiliary ground	Resistance
		Feet			Ohms
20	1-inch driven pipe	8	Filled ground	Bonded rail	17
21	¾-inch driven pipe	8	Sandy	Water pipe	120
22	do	8	do	do	59
23	1-inch driven pipe	8	do	do	75
24	¾-inch driven pipe	8	do	do	110
25	do	8	Filled ground	do	21
26	do	8	Sandy	do	85
27	1-inch driven pipe	8	do	do	130
28	¾-inch driven pipe	8	Clay and sand	do	29
29	do	8	Clay and stones	do	12
30	1-inch driven pipe	8	do	do	66
31	¾-inch driven pipe	8	do	do	95
32	1-inch driven pipe	8	Loam over sand	do	28
33	¾-inch driven pipe	8	Sandy	do	260
34	do	8	Sand, gravel, loam	do	125
35	do	8	do	do	77
36	½-inch driven pipe	8	do	do	145

DES MOINES, IOWA

1	1-inch driven pipe	9	Filled ground	Water pipe	6
2	¾-inch driven rod	8	Black, low, and wet	do	28
3	1½-inch driven pipe	8	Clay	do	14
4	do	9	do	do	9
5	do	9	do	do	10
6	do	9	do	do	6.5
7	do	10	do	do	12
8	do	9	Sandy loam, swampy	do	12
9	do	9	Clay	do	10.5
10	do	9	do	do	6

DAVENPORT, IOWA

1	1-driven pipe	10	Clay	Water pipe	7.5
2	do	10	do	do	14
3	do	10	do	do	13
4	do	10	do	do	10
5	do	10	do	do	5.5
6	do	10	Black loam over clay	do	8
7	do	10	Sandy	do	25
8	Coil of wire at foot of pole	5	Black soil	do	13
9	1-inch driven pipe	10	Clay	do	8
10	do	10	do	do	7
11	do	10	Black loam over clay	do	11
12	do	10	Clay	do	6
13	do	10	do	do	10

TABLE 13.—Resistance of Ground Connections—Continued

PEORIA, ILL.

Ground No.	Type	Depth	Soil	Auxiliary ground	Resistance
		Feet			Ohms
1	Maxum ground box	8	Clay	Water pipe	9
2	½-inch driven pipe	8	do	do	14
3	¾-inch driven pipe	8	Loam over clay	do	55
4	do	8	Clay	do	25
5	do	8	Sandy	do	45
6	½-inch driven pipe	8	Sand and gravel	do	52
7	do	8	do	do	38
8	¾-inch driven pipe	8	Sand	do	64
9	do	8	Sandy	do	34
10	½-inch driven pipe	10	Sand	do	70

CHICAGO, ILL.

1	½-inch driven pipe	8	Sandy	Water pipe	37
2	do	8	do	do	26
3	do	8	do	do	26
4	do	8	do	do	16
5	do	8	do	do	43
6	do	8	Black loam over sand	do	15
7	do	8	do	do	14
8	do	8	Clay	do	7
9	do	8	do	do	10
10	do	8	do	do	10
11	do	8	do	do	8

MILWAUKEE, WIS.

1	⅝-inch driven pipe	6	Black soil, low	Water pipe	18
2	⅝-inch driven pipe	6	Gravel and clay	do	46
3	⅝-inch driven pipe	6	Sand and gravel	do	72
4	do	6	Clay and gravel	do	58
5	do	6	Sand and clay	do	85
6	do	6	Red clay	do	42
7	do	6	Clay and gravel	do	40
8	do	6	Gravel and clay	do	38
9	do	6	Clay and gravel	do	52
10	do	6	do	do	33
11	do	6	Blue clay	do	43
12	do	6	Clay and gravel	do	25
13	do	6	Clay	do	15
14	do	6	do	do	27
15	do	6	do	do	45
16	do	6	do	do	29
17	do	6	Gravelly clay	do	43
18	do	6	Red clay and gravel	do	25
19	do	6	do	do	35

TABLE 13.—Resistance of Ground Connections—Continued

INDIANAPOLIS, IND.

Ground No.	Type	Depth	Soil	Auxiliary ground	Resistance
		Feet			Ohms
1	¾-inch driven pipe	8	Clay and gravel	Water pipe	72
2	do	8	do	do	36
3	do	8	do	do	140
4	do	8	do	do	66
5	do	8	Gravel	do	150
6	do	8	Clay	do	19
7	do	8	do	do	13
8	do	8	do	do	28
9	do	8	do	do	27
10	do	8	do	do	22
11	do	8	Clay and gravel	do	28
12	do	8	do	do	64
13	do	8	Clay	do	72
14	do	8	Clay and gravel	do	108
15	do	8	do	do	76

CINCINNATI, OHIO

1	Federal cartridge grounds, 4 in parallel	6	Sandy	Water pipe	10
2	Paragon cones, 5 in parallel	6	Sandy, on bank of canal	do	5
3	Paragon cones, 3 in parallel	6	Sandy	do	7
4	¾-inch driven pipe	6	Rocky	do	200
5	do	6	Stony	do	22
6	do	6	Gravel and clay	do	65
7	do	6	do	do	70
8	do	6	Clay	do	31
9	do	6	do	do	27
10	do	6	do	do	15
11	do	6	Clay and stones	do	37
12	do	6	do	do	51
13	do	6	Clay	do	40
14	do	6	do	do	15
15	do	6	do	do	21
16	do	6	Filled ground	do	17
17	do	6	Clay and stones	do	18
18	do	6	do	do	38
19	do	6	Clay	do	11
20	do	4	Clay and stones	do	93

DAYTON, OHIO

1	¾-inch driven pipe	6	Gravelly	Water pipe	105
2	do	6	Gravelly, moist	do	36
3	do	6	do	do	48
4	do	6	do	do	115
5	do	6	Filled ground	do	41
6	do	6	do	do	24
7	Paragon cone	6	Sandy	do	52
8	Coil of messenger wire	6	do	do	13
9	¾-inch driven pipe	6	do	do	85

TABLE 13.—Resistance of Ground Connections—Continued

DAYTON, OHIO—Continued

Ground No.	Type	Depth	Soil	Auxiliary ground	Resistance
		Feet			Ohms
10	¾-inch driven pipe	6	Filled ground	Bonded rail	19
11	do	6	do	do	32
12	do	6	Clay	Water pipe	26
13	do	6	do	do	28
14	do	6	do	Bonded rail	48
15	do	6	Clay over gravel	do	22
16	do	6	do	Water pipe	44
17	do	6	Gravelly	do	45
18	do	6	Filled ground, bank of canal.	do	55
19	do	6	Gravelly	do	90
20	do	6	Stony	do	25
21	2 by 4 foot copper plate below water level.	12	Gravelly	do	48

TOLEDO, OHIO

1	¾-inch driven pipe	12	Clay	Bonded rail	8
2	do	12	do	Water pipe	10
3	do	12	do	do	11
4	do	12	do	Bonded rail	10
5	do	12	do	do	12
6	do	12	do	Water pipe	11

DETROIT, MICH.[a]

1	1-inch driven pipe	6	Sandy	Water pipe	11.8
2	do	6	do	do	10.1
3	do	6	do	do	6.3
4	do	6	do	do	6.3
5	do	6	do	do	8.1
6	do	6	do	do	14.8
7	do	6	Loam	do	14.6
8	do	6	do	do	3.9
9	do	6	do	do	11.4
10	do	6	Clay	do	9.0
11	do	6	do	do	10.9
12	do	6	do	do	13.3
13	do	6	do	do	10.3
14	do	6	do	do	18.5
15	do	6	do	do	17.9
16	do	6	Sand	do	8.0
17	do	6	do	do	17.4
18	do	6	do	do	47.5
19	do	6	do	do	68.1
20	do	6	do	do	7.9
21	do	6	Sand and clay	do	12.1
22	do	6	do	do	9.6
23	do	6	Sandy	do	7.1
24	do	6	do	do	12.9
25	do	6	do	do	29.9
26	do	6	do	do	12.7

[a] Measurements made by the Edison Illuminating Co., of Detroit.

TABLE 13.—Resistance of Ground Connections—Continued

CLEVELAND, OHIO

Ground No.	Type	Depth	Soil	Auxiliary ground	Resistance
		Feet			Ohms
1	10 pounds No. 4 copper wire in 15 pounds coke.	5	Clay	Water pipe	19
2	do	5	do	do	90
3	do	5	do	do	25
4	do	5	do	do	21
5	do	5	Clay over shale	do	49
6	do	5	do	do	28
7	do	5	do	Bonded rail	22
8	do	5	Rocky	Water pipe	250
9	do	5	Clay over rock	do	35
10	do	5	Wet sand	do	48
11	do	5	do	do	140
12	do	5	Sand	do	160
13	do	5	do	do	94
14	do	5	do	do	95
15	do	5	do	do	275
16	do	5	do	do	140

CANTON, OHIO

1	¾-inch driven pipe	15	Clay and gravel	Water pipe	40
2	do	15	do	do	85
3	do	15	do	do	90
4	do	15	do	do	180
5	do	15	Gravel	do	300
6	do	15	do	do	150
7	do	15	do	do	190

PITTSBURGH, PA.

1	¾-inch driven pipe	8	Sandy	Water pipe	63
2	do	8	Clay over shale	do	22
3	do	8	do	do	15
4	do	8	Clay	do	36
5	Two ¾-inch driven pipes 4 feet apart.	8	do	do	28
6	¾-inch driven pipe	8	Shale	do	32
7	do	8	do	do	36
8	do	8	Stony hillside	Bonded rail	80
9	do	8	Stony	Water pipe	190
10	do	8	do	Bonded rail	50
11	do	8	Filled ground	Water pipe	21

WASHINGTON, D. C.

1	Steel pole set in concrete	5	Clay and stones	3-point method	90
2	do	5	do	do	110
3	do	5	do	do	40
4	do	5	do	do	60
5	do	5	do	do	40

TABLE 13.—Resistance of Ground Connections—Continued

WASHINGTON, D. C.—Continued

Ground No.	Type	Depth	Soil	Auxiliary ground	Resistance
		Feet			Ohms
6	Steel pole set in concrete	5	Clay and stones	3-point method	80
7	do	5	Clay, low, in hollow	do	18
8	do	5	do	do	4
9	do	5	Clay	do	29
10	do	5	do	do	33
11	do	5	do	do	8
12	do	5	do	do	53
13	do	5	do	do	17
14	¾-inch driven pipe	10	Clay and stones	Water pipe	55
15	do	10	do	3-point method	25
16	do	10	do	Water pipe	61
17	do	10	do	do	50
18	do	10	do	do	24
19	do	10	do	Bonded rail	19
20	do	10	do	Water pipe	15
21	do	10	do	do	30
22	do	10	do	do	45
23	do	10	do	Bonded rail	26
24	do	10	do	Water pipe	39

1. METHOD OF MEASUREMENT

Nearly all of the measurements were made by the bridge method. At first it was thought desirable to transport ammeters and voltmeters to use where conditions were such that the bridge would not work, but it was soon found that occasion for their application would arise infrequently, and since they are somewhat cumbersome and liable to derangement from jolting in vehicles they were abandoned in favor of the bridge instrument, which is more compact and rugged.

No great difficulty was at any time experienced with the bridge method, although it was tried under nearly every condition that is likely to arise. That is, no serious difficulties were encountered that would not also have been encountered with the ammeter-voltmeter method. In fact, the bridge gave more or less satisfactory results in places where an ammeter and voltmeter could not readily have been used, or only with difficulty. For example, it was often found desirable to measure the resistance of lightning arrester grounds where there were no low-voltage circuits within reach from which current might be taken. Under these circumstances the ammeter-voltmeter method would require an independent source of current such as a hand generator, which would

be much heavier and more inconvenient to operate than the independent source of current already described for the bridge. As another example, it was sometimes found necessary to use a bonded street-car rail as an auxiliary ground connection. Here a variable difference of potential accompanying the return of direct current from the cars usually existed between the rail and the ground under test, and when the test circuit was closed, a fluctuating direct current was superimposed upon an alternating current with the result that a greater or less distortion of the current wave took place. With the bridge this distortion made no difference, a balance being easily obtained unless the hissing sound from the commutation of the direct current obscured the sound of the bridge current, or a sufficient direct current passed through the telephone receiver to draw down the diaphragm and hold it so the vibrations caused by the bridge current were inaudible; although the chances of this occurring were not found to be great, because of 50 measurements made in this way serious interference was met with in only three or four cases. And even in those, by taking advantage of periods when the cars were evidently standing still, or when the potential difference between track and ground was at its lower values, fair results were obtained. With ammeters and voltmeters, however, if special precautions are not taken the wave distortion just mentioned may give rise to errors in current and voltage readings, especially where grounds of low resistance are being tested. With alternating current at 110 or 220 volts, and grounds under test of high resistance, the chances of error are small in most cases, but the possibility of such errors should be kept in mind. The magnitude of the discrepancies which may arise can be estimated by connecting an ammeter between the rail and the ground under test. If the flow of direct current to ground is but a few per cent of the alternating current used its effects may be neglected.

2. PROCEDURE IN MAKING TESTS

The procedure followed in each place varied somewhat according to the records available, the character of the soil, and other factors. The main point observed was to select those ground connections of the different types in use which lent themselves most readily to making measurements. On this account lightning-arrester grounds were picked out wherever possible because they were in most cases separated from all electrical circuits by

spark gaps; and, since for this reason there was no leakage, no necessity existed for cutting the ground wire and splicing it again. In some places, however, where common grounds were used, or where lightning-arrester grounds were not plentiful enough, it was necessary to resort to tests upon low-voltage circuit grounds and if there was leakage, or more than one ground on each circuit, the ground wire had to be cut and reconnected, which added considerably to the labor and consumed a great deal of time.

An effort was everywhere made to make tests in all of the different kinds of soil, in high and low ground, and in places where extraordinary conditions existed, if any were known. The soils were classified roughly, no attempt being made to go beyond stating their general character. This was usually ascertained by looking at excavations or cut banks near by, and assuming that what was seen fairly represented the soil where the electrodes were buried.

With regard to the form of the electrode it was usually necessary to rely upon the memory of the person assigned by the utility to accompany the observer, as to depth and other characteristics, because in but few instances were records available which gave this information. Where a standard type had been adhered to no difficulty was experienced, but where the type had been changed a few times the kind of electrode was not always easy to determine, so the first column in Table 13 may in some instances be in error.

In the selection of auxiliary grounds water pipes were, of course, given preference. But if these were not near enough bonded street-car rails were taken next in order, and then grounded telephone messenger cables and other objects, such as driven well casings. Very little trouble was experienced in obtaining water pipes as auxiliary grounds within city limits. From such observations as were made in these territories it does not seem that more than 5 or 10 per cent of the area covered by the electrical systems was out of reach of fire plugs or service pipes. Being within reach, here means within 325 feet, as that was approximately the length of the wire used. As mentioned heretofore, very little trouble was experienced with high-resistance joints in service pipes or fire plugs, although a few were discovered. On numerous occasions high-resistance joints were suspected, but on checking the measurements by means of other service pipes, fire plugs, or bonded rails, it was usually found that the abnormally high resistance was in the ground connection itself.

In Table 13 the resistances given include the resistance of the leads and the auxiliary ground where the auxiliaries consisted of water pipes, bonded rails, or telephone messenger cables. Where other kinds were used the resistance was determined by the 3-point method if possible. In some cases, however, only one ground besides the one being tested was available, and here the resistance of the two series is given and the character of the auxiliary described in column 4. The resistance of the leads was 0.04 ohm per foot, and as it was not often that more than 100 feet of wire was used, and in practically every case where occasion arose to use more the resistance measured was rather high, no account was taken of it. Very few measurements were made where the leads made a difference of more than 1 or 2 per cent.

3. SUMMARY OF RESULTS

The results of the tests are summarized below under the following heads: (*a*) Resistances by kinds of soil; (*b*) resistances by types of grounds; and (*c*) average, minimum, and maximum resistances by cities. In addition, under (*d*), a brief description is given of the general practice followed in grounding by the different utilities.

(*a*) Resistances by Kinds of Soil.—The average, minimum, and maximum resistances according to kinds of soil are given in Table 14. The soils are grouped as they are in column 2 because it was found that electrodes embedded in clay, shale, adobe, gumbo, loam, and loam intermixed with a small amount of sand showed resistances covering about the same range of values. The minumum and maximum values were usually found under some extraordinary condition of dampness or dryness, respectively, and indicate no more than the wide variations due to differences in moisture content which may be anticipated in soils of the same nature as far as resistivity is concerned. It should be stated, however, that the differences in this case are due to local conditions rather than to widespread changes during the period the measurements are being made, such as would ensue from rainfall. For example, ground connections were found in soil wet with waste water of some kind, which gave very low resistances, whereas others were found in buildings where moisture apparently never entered, which gave very high resistances. With regard to rainfall, in about half of the places visited it was found that during the month preceding the date of making the measurements the pre-

cipitation had been above normal. In the rest it had been below, so the average resistances are about what they would ordinarily be for the autumn months, the time when the work was done. As indicated heretofore, the resistance for spring and autumn is about the average for the year, or midway between minimum and maximum.

TABLE 14.—Resistances by Kinds of Soil

Grounds tested	Soil	Average resistance	Minimum resistance	Maximum resistance
		Ohms	Ohms	Ohms
24	Fills, and ground containing more or less refuse such as ashes, cinders, and brine waste	14	3.5	41
205	Clay, shale, adobe, gumbo, loam, and slightly sandy loam with no stones or gravel	24	2.0	98
237	Clay, adobe, gumbo, and loam mixed with varying proportions of sand, gravel, and stones	93	6.0	800
72	Gravel, sand, or stones with little or no clay or loam	554	35	2700

The chief conclusion to be drawn from the results given in Table 14 is that unless a ground connection is made in soil containing little or no sand, gravel, or stones, its protective value is likely to be very small, and even where the ground conditions are of the best, to derive a degree of protection comparable with that obtained from the use of water pipes, requires 10 to 20 grounds in parallel on each low-voltage circuit. The greater the proportions of stones, gravel, and sand, the greater the resistances, and in places where there is almost no clay or loam of some form, but all gravel and stones, protection by grounds made with electrodes of limited extent is out of the question. The only way in which high voltages can be guarded against effectively in such places is to use water pipes or, with a lesser degree of effectiveness, a common ground wire.

(*b*) Resistances by Types of Grounds.—It will be noted from Table 13 that comparatively few electrodes of forms other than driven pipes were found, and for this reason it is not possible to make a satisfactory comparison. Moreover, to determine their relative merits requires that they be installed in reasonably uniform soil, whereas with few exceptions the ground connections tested were made in soil that was not only highly nonuniform, but of different kinds. The only place where electrodes of different forms were found in soil that would admit of comparison was in Omaha, Nebr., where tests were made on 16 Garton hydro-

grounds and 14 driven pipes, 1 inch in internal diameter, and 10 feet in length, all of which were embedded in yellow clay. The average resistance of the former was 28 ohms and of the latter 14 ohms. The hydrogrounds, therefore, appear to be much inferior to the pipes. In other places a small number of Paragon cones, Federal Cartridge Ground Plates, and Maxum Ground Boxes were tested, but nothing was discovered which would change the sense of the conclusion already given in this paper, viz, that at the same expense better results can be obtained with driven pipes than with these patented devices. The same thing was found to be true of plates and coils of wire, either with coke or without.

In addition to the tests just mentioned a few were made on steel poles. The resistance of steel poles is of interest because in some instances they are used as a means of grounding lightning arresters; in others they carry high-voltage circuits, the wires of which may come in contact with them and be the cause of current flow and a rise of potential difference between pole and ground, with consequent danger to linemen and others. All but four of the poles tested were situated in the District of Columbia, of which six were set 5 feet deep in clay and stones and surrounded with concrete. The average resistance of these was found to be 70 ohms, while the average resistance of driven pipes 0.75 inch in internal diameter and 10 feet in length in the same kind of soil was 35 ohms. The rest of the poles, seven in number, were set to the same depth in the same way in rather damp clay soil that appeared to be free from stones. The average of these was 23 ohms, or somewhat more than that of pipes of the size just mentioned in soil of the same kind. Besides the poles tested in the District of Columbia, tests were made on four poles in Paterson, N. J., which were set to a depth of 5 feet in very sandy soil and surrounded with concrete. These showed an average resistance of 205 ohms, which is about the same as the resistance of driven pipes in the same locality. Steel poles, therefore, do not compare unfavorably with pipes driven in the same kind of soil, but their resistance is high enough to make them dangerous if a high-voltage circuit becomes grounded to them, and they are hardly to be regarded as suitable for grounding lightning arresters or low-voltage circuits, unless a number of them are electrically connected [46] together. In this way, however, a fair grounding system

[46] See rule 305, National Electrical Safety Code.

can be provided; that is, by running say a galvanized stranded steel cable approximately equivalent in conductance to a No. 6 copper wire from pole to pole and bolting it fast. The length required may be estimated roughly by neglecting the resistance of the cable and assuming that the total resistance to ground varies inversely as the number of poles connected together. For instance, if the resistance per pole is 100 ohms the number required to give a resistance to ground of 2 ohms would be 50, which would require a length of cable of 1.2 miles with poles spaced 120 feet apart. If the resistance per pole were less the length required would be proportionately less.

(*c*) AVERAGE, MINIMUM, AND MAXIMUM RESISTANCE BY CITIES.—In Table 15 are given the average, minimum, and maximum resistances measured in the different cities named in Table 13, and also an indication of the varieties of soil found in each place and the types of grounds upon which tests were made, or at least upon which most of them were made. In a number of places different types of grounds were found, but only the prevailing type is named. The soils ranged not only through all the varieties designated, but through mixture of them in different proportions as well. The minimum and maximum resistances, as stated heretofore, were usually found under extraordinary conditions as to soil or moisture content, or both. The minimum was in most cases encountered in some very damp place or in ground containing refuse; the maximum in some very dry place or in gravel or sand. These values, of course, are in nearly all instances exceptional, but at the same time they show the range of resistances that may be anticipated when making ground connections in soil of the different kinds encountered.

TABLE 15.—Resistances by Cities

No.	City	Soil	Type of ground	Average resistance	Minimum resistance	Maximum resistance
1	Newark, N. J.....	Clay and marsh land.....	Driven pipes.....	[a] 10	2.5	800
2	Paterson, N. J.....	Stony, clay, and sand over rock.	Pipes and steel poles.	340	20	700
3	Elizabeth, N. J.....	Clay, shale, sand, and gravel.	Driven pipes.....	51	4.5	190
4	New York, Bronx district.	Clay, gravelly, stony.....	Standpipes [b].....	17	6.0	45
5	Providence, R. I.....	Gravel, sand, a little clay and loam.	Driven pipes.....	996	30.0	2700

[a] One abnormally high value omitted from this average. (See Table 11.)
[b] Three and four inch pipes running under curb to building.

TABLE 15.—Resistances by Cities—Continued

No.	City	Soil	Type of ground	Average resistance	Minimum resistance	Maximum resistance
6	New Haven, Conn.	Gravel, sand, some clay	Driven pipes	23	15.0	920
7	Boston, Mass.	Gravel, sand, clay	do	548	7.0	2250
8	Philadelphia, Pa.	Clay, marsh, stony	do	133	5.8	1400
9	Scranton, Pa.	Gravel, clay, stones	do	162	19.0	490
10	Omaha, Nebr.	Yellow clay	Driven pipes and hydrogrounds.	22	3.5	60
11	Denver, Colo.	Clay, gravel, sand	Driven pipes	60	7.0	210
12	Colorado Springs, Colo.	Sand, gravel, adobe	do	92	13.0	350
13	Pueblo, Colo.	Sand, adobe, stones	do	35	3.5	210
14	Leadville, Colo.	Stones, sand	Coils wire in coke.	66	25.0	200
15	Salt Lake City, Utah.	Gravel, sand, stones, and clay.	Driven pipes	61	5.5	210
16	Butte, Mont.	Sand, gravel, stones, and clay.	Coils of wire	112	17.0	380
17	Helena, Mont.	Sand, stones, clay	Driven pipes	90	21.0	205
18	Moorhead, Minn.	Black loam over clay	Pipes and cones	28	7.0	90
19	Minneapolis, Minn.	Gravel, sand, clay, stones	Driven pipes	114	7.0	490
20	Des Moines, Iowa	Clay	do	11	6.0	28
21	Davenport, Iowa	Clay and loam	do	11	5.5	25
22	Peoria, Ill.	Gravel, sand, clay	do	40	9.0	70
23	Chicago, Ill.	Clay, sand	do	19	7.0	43
24	Milwaukee, Wis.	Clay, gravel, sand	do	40	15.0	85
25	Indianapolis, Ind.	Clay and gravel	do	61	13.0	150
26	Cincinnati, Ohio.	Sand, clay, stones	do	39	11.0	200
27	Dayton, Ohio.	Sand, gravel, clay, and stones.	do	50	13.0	115
28	Toledo, Ohio.	Clay	do	10	8.0	12
29	Cleveland, Ohio.	Clay, shale, stones, sand	Coils wire in coke.	99	19.0	275
30	Canton, Ohio.	Clay, gravel, sand	Driven pipes	133	40.0	300
31	Detroit, Mich.	Clay, sand, loam	do	15	3.9	68
32	Pittsburgh, Pa.	Clay, shale, stones, sand	do	43	15.0	190
33	Washington, D. C.	Clay, stones	Pipes, steel poles	40	4.0	110

The data of greatest interest are those showing the average resistances. These averages were calculated without regard to the type of ground, and are simply the result of averaging all of the values obtained in each place. No account was taken of the type of ground because, in the first place, by far the greater part of the grounds tested were made with driven pipes of a limited range of sizes between which there is not a wide difference of resistance if driven in the same kind of soil, and, in the second place, those grounds tested which were made with electrodes other than pipes were few in number, and experiments made at the Bureau of Standards have shown that their resistances are not greatly different from those of pipes of the average length and size described in Table 13. Hence, little effect would be produced by making al-

lowances for the differences in size and shape of the electrodes; at least not enough to change any conclusions that might be drawn. The averages are, therefore, calculated from the results as they were obtained with no attempt at correction.

These averages show that in all but eight of the places named it is not practicable to make ground connections with single electrodes of limited extent having a resistance of less than 25 ohms each. In none of them is it possible to obtain a degree of protection comparable with that which can be had from water pipes except at an expense which in all but a few cases would be prohibitive. That is, the number of electrodes in parallel required to give a total resistance to ground of 0.25 ohm, the average resistance of water pipe grounds, would be so great that only in exceptional instances would it be practicable to install them. For example, in places where the average resistance of driven pipe grounds is 10 ohms, to obtain a resistance ot 0.25 ohm would require 40 driven pipes in parallel; where the average resistance is 50 ohms the number of driven pipes would be 200, and so on. To install any such number of pipes on the average low voltage circuit is, of course, out of the question. The difficulty can be overcome to a greater or less extent by the use of a common ground wire, but even here the degree of protection afforded is not by any means equal to that of water pipes unless the common ground wire is itself connected to a water system and should be resorted to only where the latter are out of reach.

(*d*) General Practice in Grounding Secondary Circuits.—In the following cities water pipes are used, with driven pipes and other grounds installed, either as a measure supplementary to the use of water pipes or in places where the latter are not available: Newark, Paterson, Elizabeth, N. J.; New Haven, Conn.; Providence, R. I.; Boston, Mass.; Denver, Colo., and Canton, Ohio.

In Canton connection to the water system is made by running a wire down the pole and clamping it to the service pipe near the main. In all of the others connections to the pipes are usually made within the customer's premises. In New York City, Bronx district, a common ground wire is in use which is grounded to water pipes at all substations, and also to about 1500 "stand pipes" which contain service wires running under the curb to buildings. This common ground wire is formed by linking together the middle wires of all the low-voltage circuits which thus form a network over the whole secondary system.

In Butte, Mont., and Scranton, Pa., the type of ground most used is a coil consisting of about 10 turns of No. 4 wire stapled to the butt of the pole. In Leadville, Colo., and Cleveland, Ohio, coils of wire are also used, but instead of being stapled to the pole are embedded in about 15 pounds of coke at the foot of it. In all the other places visited driven pipes were used, with the exception of an occasional patented device, plate, local water system, or driven well casing. In Orange, Conn., near New Haven, a common ground wire has been installed consisting of a No. 6 copper wire run on top of poles, and connecting a large number of widely separated secondary circuits which are situated out of reach of water pipes and are grounded to driven pipes, local water systems, and well casings. Grounds are also placed at advantageous points along the line. The resistance, as determined by the bridge method, is less than 2 ohms, and it appears that the protection is next in degree, at least, to that afforded by water pipes.

There was a considerable variety in the methods of attaching wires to pipes, but the prevailing one seemed to be that of plugging the pipe about 4 inches below the top, inserting the wire, and pouring the pipe full of melted solder. This makes a very efficient and solid joint of good electrical conductance. Another method consisted in the use of "ground caps," which were made to fit over the top of the pipe with a longitudinal groove to receive the wire, and were driven on. In a few cases wires were attached by means of lugs which screwed on to the top of the pipe; in others by clamps, such as are commonly used for attaching ground wires to service pipes.

The use of molding to protect the ground wire from mechanical injury is not by any means universal. In many places no protection whatever is given, wire with weatherproof insulation being simply stapled to the pole. In other places, however, molding is erected which extends to the cross arm. The use of molding, or better yet, of insulating tubing, is especially to be recommended, both as a means of preventing breakage and, what is equally if not more important, as a means of protecting persons from electric shock. The possibility of breakage, of course, is not great, but it exists, especially in exposed places, and must be guarded against. Theft is another thing which must also be guarded against, and here molding may be of some assistance, especially against theft by small boys; but the best method of discouraging that practice is by the use of iron ground wires instead of copper. This reduces

the junk value of the material to such an extent that it is hardly worth while to carry it away, and yet the iron will serve as well as the copper and be stronger for the same conductance, but will not resist corrosion as successfully.

Not a few places were discovered in the course of the work where the practice existed of using a common ground for lightning arresters and secondary circuits. By far the greater number of the utilities consulted, however, disapproved of that practice. In two places where 3-phase, 4-wire 4000–2300 volt-distributing systems were used, the neutral wire was grounded at intervals, and this grounded neutral wire used in turn for grounding secondary circuits and lightning arresters. A low resistance to ground is provided in this way if the system is extensive, but there is a possibility of trouble in that the neutral wire may break, in which case, if a near-by secondary is grounded, as they usually are in this case, current at 2300 volts may flow to ground over the secondary circuit with the attendant possible dangers.

With regard to inspection, testing, and other matters pertaining to the practice of grounding, attention is directed toward Appendix I, which gives a summary of a large number of letters from electric utilities answering questions regarding their methods of protecting against high voltages.

In conclusion, the Bureau wishes to acknowledge the cordial cooperation and assistance of the following electrical utilities in obtaining the data compiled above:

Colorado.—Denver Gas & Electric Co., Denver; Colorado Springs Light, Heat & Power Co., Colorado Springs; Arkansas Valley Railway, Light & Power Co., Pueblo; The Colorado Power Co., Denver.

Connecticut.—The United Illuminating Co., New Haven.

District of Columbia.—Potomac Electric Power Co., Washington.

Illinois.—Central Illinois Light Co., Peoria; Commonwealth Edison Co., Chicago.

Indiana.—Merchants Heat & Light Co., Indianapolis.

Iowa.—Des Moines Electric Co., Des Moines; People's Light Co., Davenport.

Massachusetts.—The Edison Electric Illuminating Co., Boston.

Michigan.—The Detroit Edison Co., Detroit.

Minnesota.—Municipal Water & Light Plant, Moorhead; The Minneapolis General Electric Co., Minneapolis.

Montana.—Montana Power Co., Butte; Helena Light & Railway Co., Helena.

Nebraska.—Omaha Electric Light & Power Co., Omaha.

New Jersey.—Public Service Electric Co., Newark,

New York.—New York Edison Co., New York City.

Ohio.—The Union Gas & Electric Co., Cincinnati; The Dayton Power & Light Co., Dayton; Toledo Railway & Light Co., Toledo; Canton Electric Co., Canton; The Cleveland Electric Illuminating Co., Cleveland.

Pennsylvania.—The Philadelphia Electric Co., Philadelphia; Scranton Electric Co., Scranton; Duquesne Light Co., Pittsburgh.

Rhode Island.—Narragansett Electric Lighting Co., Providence.
Utah.—Utah Power & Light Co., Salt Lake City.
Wisconsin.—Milwaukee Light, Heat & Traction Co., Milwaukee.

XI. SUMMARY

The substance of this circular and the conclusions from it may be summarized as follows:

1. The resistance of a ground connection made with an electrode of limited extent depends directly upon the resistivity of the surrounding soil and also upon the form and arrangement of the electrode. The effect of the latter varies inversely as the electrostatic capacity in free space of the electrode and its image above the surface of the ground. The most advantageous form and arrangement are obtained when the electrostatic capacity is a maximum, since the latter enters as a factor in the denominator of the formula for the resistance of a ground connection. (See Appendix III.)

2. Contact resistance between clean metal and packed earth and also between rusty metal and packed earth is negligible as far as practical purposes are concerned. Where contact resistance of considerable magnitude exists it is in most cases due to paint, scale, or some impervious nonconducting material on the surface of the electrode.

3. Danger to life from electrical systems arises because of the occasional entrance of abnormally high voltages upon the low-voltage parts of electrical circuits and equipment, to which persons have access, through faults in insulation between high-voltage and low-voltage circuits. Such faults are developed for the most part by lightning and breakage of wires in storms, occasionally by high-voltage surges or deteriorated insulation.

4. The magnitude of the potential differences against ground which may appear upon low-voltage circuits or parts of equipment is governed by a number of factors, chiefly, however, by the voltage of the line with which contact is made and the relative location of the point of failure. For instance, with a 2200-volt distribution circuit feeding a low-voltage circuit through a step-down transformer a failure of insulation at an end turn of the high-voltage winding may raise the potential of the lighting circuit against ground to a value approaching 2200 volts unless provision is made for preventing it. A similar condition may arise with any low-voltage circuit if it makes contact with a high-voltage circuit.

5. Danger from high potentials between low-voltage circuits or parts of equipment and ground can best be averted by grounding the parts affected. For a high degree of safety to life the resistance of the ground connection should be such that with a current flow equal to the rated current of the nearest circuit breaker which will operate to disconnect the equipment or circuit concerned from the source of the dangerous voltage in the event of an accident to insulation, the potential difference between ground wire and ground will not exceed 150 volts, if the ground wire or circuit is accessible. Where both ground wires and circuits are inaccessible a higher voltage limit is permissible.

6. As a safety measure more adequate means should be provided for detecting accidental grounds on low-voltage circuits than is usually the case. The practice of cutting off protective grounds to avoid annoyance from accidental grounds and leaving them off indefinitely is hazardous, both to life and property, and should be discontinued. Where accidental grounds are discovered the party responsible for the operation of the circuit should be required to put it in safe working condition within a reasonable time.

7. The frames of all electrical machines that are connected, either directly or through transformers, to high-voltage lines should be grounded. Furthermore, for the reason that there is great uncertainty as to the maximum voltage that is not dangerous to life, it is desirable in all but one or two cases to ground the frames of machines operating upon lines of all voltages, unless it be those furnishing power at 150 volts or less in places where there are no inflammable nor explosive substances. An exception is where work must be done on brushes when they are alive. Here it may be well to insulate the frames at least while work is being done.

8. The frames of certain types of railway power-house switchboards should be insulated, or at least isolated, from ground, especially where earth return is used. The practice of grounding them to "fix" their potentials should be discontinued. For this amounts practically to connecting them to the negative bus bar, and severe accidents may occur when work is being done on live conductors at the back of the board through tools slipping and coming in contact with positive conductors and frame at the same time, unless spacings are great enough to prevent it or guards for live parts are provided.

9. For different classes of apparatus separate ground wires should be used, but more especially for those classes which have to do with protection against lightning. Moreover, if electrodes of limited extent are used, separate ground connections should also be provided, spaced not less than 6 feet apart. The reason for this is that if more than one class of apparatus is connected to the same ground wire a flow of current from one may cause a rise of potential against ground which is impressed upon all the rest. The greatest danger in this respect is to be expected from lightning arresters.

10. Water pipes offer by far the most desirable means of making ground connections, but where it is necessary to resort to other means, such as driven pipes or plates, an appreciable degree of protection can in some cases be obtained at reasonable expense. In a great many cases, however, grounds of the latter type will be found unsatisfactory. If a common ground wire is used a good degree of protection can be had, but the expense may be considerable, and the result not equal to that obtainable from water pipes, unless the common ground wire is connected to a water pipe.

11. There is no danger to water pipes of electrolysis by such stray alternating currents as may result from grounding low-voltage alternating-current circuits.

12. Low-voltage alternating-current circuits should be grounded at two or more points; from the standpoint of safety to life the more the better.

13. Ground connections for direct-current systems should be confined to one at the station.

14. Where it is allowable to ground a low-voltage circuit to pipes at more than one point, such grounding should be confined to a single pipe system, except where no electric railway with earth return is in operation, or there is no possibility of potential differences existing between metallically separate pipe systems. Moreover, there should be no insulating or other high-resistance joints between the points of connection to the pipe; for if there are the wires will act as a shunt to them and may thus carry a heavy flow of stray current from street railways, and in a measure nullify the effect of the joint.

15. Danger to employees of the water utility because of circuits being grounded to water pipes is practically nonexistent where multiple ground connections are used. Where there is a

single connection to a pipe, a remote possibility of danger exists, but this can readily be averted by requiring the electric company to disconnect the wire before work is begun on the pipes and to reconnect it after the work is done.

16. The resistance of ground connections made with electrodes of limited extent may vary with seasons to the extent of several hundred per cent. These changes are caused by changes in the temperature and moisture content of the soil.

17. The resistance of water-pipe ground connections varies but slightly with the seasons. This is due to the fact that a large part of the total resistance of such ground connections is contributed by the joints of the pipe itself, which are of relatively constant resistance, while only a small part of the total resistance is contributed by the soil, which is extremely variable. Changes in the moisture content and temperature of soil, therefore, produce but slight changes in the total resistance of water-pipe ground connections.

18. The resistance of ground connections made with electrodes of limited extent may be greatly decreased by salting, or dissolving any substance in the soil water surrounding the electrode which decreases its resistivity.

19. Ground connections can dissipate energy at a limited rate. This rate depends upon the moisture content of the soil, the rate at which moisture will travel by capillary action and the distance which it will cover, the size of the electrode, and other factors. If it is exceeded, drying of the soil will occur with a great increase of resistance. A pipe driven to a depth of 10 feet in moist, moderately salted earth may be estimated as having capacity to dissipate energy at a rate from 5 to 20 kw without an increase of resistance.

20. When current flows through a ground connection a potential gradient exists in the surrounding surface of the ground. For electrodes of limited extent, such as driven pipes and plates, its value varies roughly as the inverse square of the distance from the electrode, and directly as the current in amperes. There is not much danger to persons from the resulting potential differences if the safety requirements in regard to resistance are complied with unless it be that between ground wire and ground; but danger from this can readily be averted by covering the ground wire with insulating material. There is, however, some danger to animals from the potential differences in the ground, and much

trouble can be avoided by keeping such trespassers away from ground connections by fencing or by other means.

21. Substantial construction is one of the first considerations in making ground connections and should never be sacrificed to expediency. Unless workmanship and materials are of the best the protection afforded may be inadequate and unreliable.

22. It is desirable to maintain at all times the continuity of the connection to ground. Ground wires should, therefore, be carefully protected from mechanical injury. In line with this, ground connections to water-service pipes should be made at the point where there is the least likelihood of the pipe being disconnected between the point of attachment of the ground wire and the main. If the water meter is between the ground wire and the main a jumper of the same size as the ground wire should be put around it. If a ground wire needs to be disconnected this should be done by the electric-service company, and subsequently be reconnected by it.

23. The general practice in regard to circuit ground wires is to use No. 6 copper as a minimum size. Experience indicates that this is of sufficient mechanical strength. The current-carrying capacity required of a ground wire or of several in parallel is determined by the current rating of the nearest cut-out which will operate to break the circuit in the event of an accident to insulation.

24. Ground connections should be inspected at intervals not exceeding a year. Even shorter intervals are preferable. In no case should inspection be omitted, for it is unsafe to leave a ground connection without attention.

25. When a ground connection is installed its resistance should be measured. Reasonable assurance should also be had that it will carry the maximum current likely to flow through it without drying the soil and causing an increase of resistance. Subsequent tests may be confined to resistance measurements, say once in four years on driven pipes, once in two years on plates, and once in every year on salted ground connections.

26. For making resistance measurements the ammeter-voltmeter method with alternating current is the most accurate, but is in many cases inconvenient for field work. Where alternating current is not available from service lines, good results may be obtained with direct current, or with a Kohlrausch bridge, using an easily portable source of alternating or oscillating current.

Testing with lamp banks or fuses should be confined to ascertaining whether ground wires are continuous, and to similar purposes. Testing with magnetos should be abandoned, and testing with a voltmeter should not be relied upon for more than a bare indication of the condition of a ground connection.

27. Experience has not shown that grounding newly installed low-voltage circuits increases the fire hazard from them, nor has it shown that the interference with service caused by grounding is a factor that needs seriously to be reckoned with. On the contrary, the safety secured to life and property from high voltage appears to be all clear gain. In grounding old work the hazard is not increased unless the insulation on the ungrounded wires is very weak, and is decreased if the insulation has failed to a sufficient extent to blow fuses and reveal the trouble at the time the ground connections are made.

28. On account of the danger of fires or explosions, gas pipes should not be used for grounding except in special instances where the possibility of even slight current flow is negligible. Moreover, the almost invariable presence of water pipes makes connection to gas pipes unnecessary.

29. Because of the great advantage to the public, and the slight disadvantage, if any, to the public-service corporations resulting from grounding to water pipes, such grounding should be made compulsory in cases where it is necessary to protect human life. There is, moreover, a joint responsibility between the several public-service companies concerned, because both contribute to the life hazard by running their pipes and circuits near each other within buildings.

30. One hundred and seven of the 418 companies communicated with in the course of this investigation place the cost of making ground connections from $2 to $5. Other sources of information place the cost from $5 to $15. The available data on costs, however, are insufficient to enable a dependable estimate to be made.

31. Specifications for ground connections should be based upon the results which it is necessary to produce, rather than upon arbitrary methods of construction, as has been the custom to a large extent in the past.

32. Measurement of the resistance of ground connections made with driven pipes and other forms of electrodes of limited extent as now used in different parts of the country show that it is difficult thus to obtain adequate protection from high voltages even where

soil conditions are the most favorable. And where conditions are unfavorable, as where there is a great deal of gravel and sand, adequate protection is ordinarily not obtainable except by the use of water pipes, or a common ground wire. The latter, however, is subject to breakage the same as a line wire, which may destroy the protection; and at the same time, even where there is no danger of breakage, the degree of safety is not as great as that afforded by water pipes.

WASHINGTON, October 3, 1917.

30263°—18——14

APPENDIXES

Appendix I.—SUMMARY OF CORRESPONDENCE WITH ELECTRIC COMPANIES ON GROUNDING

Below is given a brief summary of answers to questions addressed to a large number of electric-service companies in the United States on grounding. The results of this correspondence are given here as indicating the present status of the practice of grounding to avert dangers from electrical systems. They show that although earthing is quite general, many operators are not convinced of its efficacy as a preventive of accidents to life and property, and also that as it is now practiced it is in many cases of questionable worth as a measure of safety.

Total number of electric-service companies from which replies were received	418
Q. 1. Do you believe grounding desirable?	
Yes	271
No	62
Doubtful	14
Conditional	29
No replies	42
Q. 2a. What percentage of low-voltage direct-current circuits do you ground?	
One hundred per cent	66
Less than 100 per cent	9
None	118
At station only	3
Having railway circuits only	2
Mine work only	1
No direct-current circuits	157
No replies	62
Q. 2b. When did you begin?	
1915	5
1914	5
1910–1913	14
Prior to 1910	24
Prior to 1900	11
No direct-current circuits	157
No replies	202
Q. 3a. What percentage of 110–220 volt circuits do you ground?	
One hundred per cent	199
Fifty per cent or more	18
Less than 50 per cent	31
Q. 3a—Continued.	
None	128
All new installations	3
All large transformers	1
No alternating-current circuits	1
No replies	37
Q. 3b. When did you begin?	
1915	16
1914	38
1910–1913	99
Prior to 1910	64
Prior to 1900	4
No alternating-current circuits	1
No replies	196
Q. 4a. What percentage of 110–220–440 2 or 3 phase circuits do you ground?	
One hundred per cent	85
Fifty per cent or more	6
Less than 50 per cent	6
One hundred per cent of 110–220 volt circuits	22
Twenty-five per cent of 110–220 volt circuits	1
Four hundred and forty volt circuits	2
No 2 or 3 phase circuits	213
Neutrals of all transformers	1
Conditional	1
No 2 or 3 phase circuits grounded	15
No replies	67
Q. 4b. When did you begin?	
1915	8
1914	18
1910–1913	52

Q. 4b—Continued.
- Prior to 1910 23
- Prior to 1900 2
- No 2 or 3 phase circuits 15
- No replies 300

Q. 4c. In your experience and belief is this a good practice?
- Yes 175
- No 66
- Doubtful 13
- Conditional 11
- No replies 153

Q. 5. How frequently do you make grounds on each secondary?
- Each transformer 109
- Transformer and also at services 10
- Each service 24
- Transformer and at intervals of 250 to 1000 feet of line 8
- Irregularly, 250 to 1000 feet 71
- More than 1000 feet apart 4
- In manholes 2
- Common ground wire 2
- No replies 188

Q. 6a. How often do you inspect grounds?
- Intervals of 2 to 5 years 3
- Intervals of 1 to 2 years 5
- Intervals of 1 year 81
- Intervals of 6 months or less 43
- No systematic inspection 59
- No inspection of any kind 12
- No replies 215

Q. 6b. How often do you test them?
- Intervals of 2 to 5 years 3
- Intervals of 1 to 2 years 1
- Intervals of 1 year 31
- Intervals of 6 months or less 18
- Not systematic 35
- None of any kind 47
- Answering "yes," without stating interval 23
- No replies 260

Q. 7. Is grounding required by ordinance in your city?
- Yes 29
- No 302
- Required by State law 3
- No replies 84

Q. 8. Do you ground at poles or within buildings, or both?
- At poles 165
- In buildings 33
- Both 65
- Manholes 3
- Common ground wire 2
- No replies 151

Q. 9a. In how many cases have you found that grounding protects from primary or other crosses?
- Yes 2
- One to three 30
- Three to ten 11
- More than 10 4
- Several 14
- Many 15
- All 5
- No record or no crosses 79
- No replies 258

Q. 9b. Have persons been injured or killed on your grounded circuits?
- Yes 20
- No 231
- No replies 167

Q. 9c. Have fires resulted from grounding?
- Yes 14
- No 222
- No replies 182

Q. 10a. Do you ground on water or gas systems or both?
- Water 115
- Gas 2
- Both 24
- Neither 99
- No replies 178

Q. 10b. Do you use other types of ground? If so, what?
- No 4
- Driven pipes 123
- Buried plates 33
- Driven rods 37
- Cones, or cones and pipes, rods or rails 20
- Pipes and plates 19
- Pipes and rail 7
- No replies 175

Q. 11. Does the water company or water department object to grounds on its system?

Yes	48
No	196
Ordinance against it	3
Not known	10
No replies	161

Q. 12. What is your average expense for making a ground?

Between $1 and $2	59
Between $2 and $5	107
Between $5 and $10	23
More than $10	5
No replies	224

Q. 13. What is your average expense for maintaining a ground?

Between 10 and 25 cents	10
Between 25 cents and $1	17
Between $1 and $3	1
Between $3 and $5	1
No replies	389

Q. 14. How deep do you place grounds other than those on piping systems?

Between 3 and 6 feet deep	83
Between 6 and 10 feet deep	104
Between 10 and 20 feet deep	44
More than 20 feet deep	3
No replies	184

Q. 15a. For what length of time do you find your average ground continues suitable?

From 2 to 4 years	11
From 4 to 8 years	9
From 8 to 12 years	12
More than 12 years	2
No replies	384

Q. 15b. For what current do you find your average ground suitable?

Five to 20 amperes	14
Twenty to 50 amperes	8
Fifty to 100 amperes	10
Capacity of wire	1
No replies	385

Q. 16a. What electrical resistance do you obtain on your grounds?

Less than 1 ohm	5
One to 5 ohms	4
Five to 20 ohms	15
Twenty to 50 ohms	5
More than 50 ohms	5
No replies	384

Q. 16b. This resistance is based on what current passing and for what length of time?

One to 5 amperes	9
Five to 10 amperes	4
Ten to 30 amperes	7
No replies	398

Q. 17a. What increase of resistance do you find on grounds after one year?

No increase	9
Slight increase	2
Fifty per cent increase	1
Decrease	2
No replies	404

Q. 17b. After five years?

Very little	1
None	5
No replies	412

Q. 18. What current-carrying capacity do you provide for your grounds?

Twenty to 50 amperes	18
Fifty to 100 amperes	48
One hundred to 500 amperes	5
Capacity of transformer	1
Same as line	4
No replies	342

Q. 19. How much are you bothered with electrolysis from earth currents in your ground connections?

None	179
Slight	16
Some	4
No replies	219

Q. 20. What size of ground wires do you use?

No. 14	1
No. 8	3
No. 6	130

Q. 20—Continued.

No. 4	59
No. 3	1
No. 2	3
No. 00	4
No. 0000	1
No. 6 to 3/0	1
No. 6 to No. 4	27
No. 2 to No. 6	2
No. 4 to No. 8	1
No. 6 to No. 00	1
No. 6 to No. 0	3
No. 2 to No. 4–No. 6	3
No. 2 to No. 4	1
No. 6 to No. 8	2
No. 8 to No. 0	1
No. 4 to 500 000 cm	2
No. 6 to 0000	3
No. 4 to No. 10	1
No. 1 to No. 4	1
No. 9 Fe	1

Q. 20—Continued.

Seven-strand iron cable	1
Five-sixteenths inch iron	1
No. 6 BB	2
Capacity of transformer	1
Same as secondary	5
Same as line	2
Same as neutral wire	1
No replies	152

Q. 21. Do you approve of grounding low-voltage circuits to conduit containing wires in buildings, utilizing the conduit ground wire as the ground for the circuit?

Yes	55
No	145
Conditional	14
Doubtful	4
No replies	200

Appendix II.—RULES COVERING METHODS OF PROTECTIVE GROUNDING OF CIRCUITS, EQUIPMENT AND LIGHTNING ARRESTERS FOR STATIONS, LINES, AND UTILIZATION EQUIPMENT, BEING SECTION 9 OF THE NATIONAL ELECTRICAL SAFETY CODE

CONTENTS

Rules covering methods of protective grounding:
- 90. Scope of the rules.
- 91. Application of the rules.
- 92. Where ground conductor shall be attached.
- 93. Ground conductor.
- 94. Nature of ground connection.
- 95. Method.
- 96. Ground resistance.
- 97. Joint use of grounds and ground conductors for different systems.

Discussion of the Rules.

90. Scope of the Rules

The following rules apply to all lightning arrester grounding and to the grounding of all circuits, equipment, or wire runways, when the grounding is intended to be a permanent and effective protective measure. These rules do not require that grounding shall be done, but cover the methods for protective grounding. The rules requiring grounding, in accordance with the methods specified below, are included under parts 1, 2, 3, and 4 of the National Electrical Safety Code.

Other methods of construction and installation than those specified in the rules may be used as experiments to obtain information, if done where supervision can be given by the proper administrative authority.

The following rules do not apply to the grounding of arresters on signal circuits to the grounded return of trolley or third-rail systems, nor to the grounding of lightning protection wires where these are not connected to electrical circuits or equipment.

91. Application of the Rules and Exemptions

(*a*) The rules are intended to apply to all such installations, except as modified or waived by the proper administrative authority or its authorized agents, and are intended to be so modified or waived in particular cases whenever any rules are shown to involve expense not justified by the protection secured, or for any other reason to be impracticable, or whenever it is shown that equivalent or safer construction can be more readily provided in other ways.

(*b*) The intent of the rules will be realized (1) by applying the rules in full to all new installations, reconstructions, and extensions, except where any rule is shown to be impracticable for special reasons, or where the advantage of uniformity with existing construction is greater than the advantage of construction in compliance with the rules; (2) by placing grounds on existing installations or bringing present grounds into compliance with the rules, except where the expense involved is not justifiable.

The time allowed for bringing existing installations into compliance with the rules will be determined by the proper administrative authority.

(*c*) It will sometimes be necessary to modify or waive certain of the rules in case of temporary installations or installations which are shortly to be dismantled or reconstructed.

(*d*) In cases of emergency or pending decision of the administrator the person responsible for the installation may decide as to modification or waiver of any rule, subject to review by proper authority.

92. Where Ground Conductor Shall be Attached (When Grounding is Required by this Code, or is Installed as a Protective Measure, See Rule 304)

(*a*) Direct-Current Distribution Systems.—The neutral of three-wire direct-current systems shall be grounded at one or more supply stations, but not at individual services nor within buildings served. One side of a two-wire direct-current system may be grounded, but at one station only.

In three-wire systems the neutrals entering any junction box should be bonded together, but the box should not be specially grounded.

In two-wire systems the grounded side of the circuit should be insulated from ground except at the station ground connection.

(*b*) Alternating-Current Distribution Systems.—All secondary distribution systems shall be grounded at the building services or near the transformer (or transformers) either by direct ground connection (through water-piping system or artificial ground, see rule 94) or by the use of a system ground wire to which are connected the grounded conductors of many secondary mains and which is itself effectually grounded at intervals that will fulfill, for any secondary utilizing the system ground wire, the resistance and current-carrying requirements of rule 96a.

Single-phase, three-wire distribution systems shall be grounded at the neutral conductor. Two-wire, single-phase systems shall be grounded at the neutral point or on either conductor. Two-wire, single-phase and two or three phase systems shall, in general, be grounded at that point of the system which brings about the lowest voltage from ground of unguarded current-carrying parts of connected devices and also permits most convenient grounding.

Where any phase of a two or three phase system is used for lighting, that phase should be grounded and at the neutral conductor, if one is used.

In the absence of direct grounds at all building services, ground connections shall be made to the grounded neutral or other grounded conductor of a secondary system supplying more than one utilization equipment at intervals that will fulfill the resistance and current-carrying requirements of rule 96a.

Where the secondaries of transformers are supplying a common set of mains the fuses shall be installed only at such points as will not cause the loss of the ground connections after the fuses in the transformer circuits or mains have been blown.

Multiple grounds are preferable in all cases, because of the assurance provided against loss of the protection afforded by the chance disconnection of any ground connection.

Grounds other than the single-ground connection at the building service shall not be made to alternating-current secondaries within the buildings served.

(*c*) LIGHTNING ARRESTERS.—The connection to a lightning arrester shall be at such a point that its ground conductor is as short and straight as practicable.

Ground conductors for lightning arresters should not pass through iron or steel conduits unless electrically connected to both ends of such conduits.

(*d*) EQUIPMENT AND WIRE RUNWAYS.—The point at which the ground conductor is attached to equipment or wire runways shall, if practicable, be readily accessible.

93. Ground Conductor

(*a*) MATERIAL AND CONTINUITY.—The ground conductor shall be of copper or of other metal which will not corrode excessively under the existing conditions and, if practicable, should be continuous. Joints shall be so made and maintained as to conform to the resistance and current-carrying capacity requirements of rule 96.

Ground connections from circuits should not be made to jointed piping within buildings, except that water piping outside of meters and beyond any point which is liable to disconnection may be used. (See rules 94*a*, 95*a*, and 95*b*.)

No automatic cut-out shall be inserted in the ground conductor or connection except in a ground connection from equipment where its operation will immediately result in the automatic disconnection from all sources of energy of the equipment so grounded; no switch shall be so inserted except in plain sight, provided with distinctive marking and effectively isolated from unqualified persons. (See also rule 92*b*, par. 4.)

(*b*) SIZE AND NUMBER.—For grounding circuits the ground conductors shall have a combined cross section (and current capacity) sufficient to insure the continuity of the ground connection and its continued compliance with rule 96*a*, under conditions of excess current caused by accidental grounding of any normally ungrounded conductor of the circuit. No individual ground conductor for electrical circuits shall have less current capacity than that of a No. 6 copper wire, except that for additional grounds after the first on any circuit, smaller ground wires may be used, provided that they are in no case smaller than the conductor to which they are attached nor smaller than No. 10 copper.

For lightning-arrester ground connections the ground conductor or conductors shall have a current-carrying capacity sufficient to insure continuity of the ground connection under conditions of excess current caused by or following discharge of the arrester. No individual ground conductor shall be smaller than a No. 6 wire.

For electrical equipment the current-carrying capacity of a ground conductor shall be not less than that provided by a copper wire of the size indicated in the following table. When there is no cut-out protecting the equipment, the size of ground conductor will be determined by the design and operating conditions of the circuit.

Capacity of nearest automatic cut-outs:	Required size ground conductor American Wire Gauge
200 to 500 amperes	4
100 to 200 amperes	6
30 to 100 amperes	10
10 to 30 amperes	14

In portable cord to portable equipment protected by fuses not greater than 10-ampere capacity, a No. 18 ground wire may be used.

(*c*) MECHANICAL PROTECTION AND GUARDING AGAINST CONTACT.—Where exposed to mechanical injury the ground conductor shall be protected by substantial conduit or other guard. Guards for lightning-arrester ground conductors should be of non-magnetic material unless the ground conductor is electrically connected to both ends of the guard.

If the resistance of the ground connection is in excess of the values in rule 96 for water-pipe grounds, the ground conductor except in rural districts shall be protected

and guarded by being inclosed in insulating conduit or molding to protect persons from injury by coming into contact with it.

Such a high resistance may exist where artificial grounds are necessarily permitted in lieu of the preferable grounds to buried metallic water-piping systems.

Mechanical protection and insulating guards should extend for a distance of not less than 8 feet above any ground, platform, or floor from which ground conductors are accessible to the public. (See also rule 246.)

Insulating mechanical protection is advisable for single-arrester grounds, even when the connection is made to a water-piping system, and has therefore a low resistance, since a single connection is liable to be accidentally broken.

Even where ground connections have a resistance not exceeding that specified in rule 96 and no guard is therefore provided (or as an additional protection to persons even where guards are used) artificial grounds may be arranged to minimize the potential gradient along the surface of the earth by use of radial connecting wires underneath the earth surface or by other suitable means.

A circuit ground conductor shall be guarded as required for current-carrying conductors of the circuit, unless the ground conductor is entirely outside buildings, has strength and current capacity not less than that of No. 6 copper wire, and the circuit is elsewhere grounded by other ground conductors, except that in stations substantial bare ground busses may be used.

(*d*) UNDERGROUND.—Wires used for ground conductors, if laid underground, shall, unless otherwise mechanically protected, be laid slack to prevent their being readily broken, and shall have joints carefully painted or otherwise protected against corrosion.

94. Nature of Ground Connection.

The ground connection shall be permanent and effective and be made as indicated in (*a*), (*b*), or (*d*) below; always as in (*a*), if (*a*) is available (except as per rule 97*b*).

(*a*) PIPING SYSTEMS.—For circuits, equipment, and arresters at supply stations, connections shall be made to all available active continuous metallic underground water-piping systems between which no appreciable difference of potential normally exists, and to one such systems if appreciable differences of potential do exist between them. At other places connections shall be made to at least one such system, if available. Gas piping should not be used. (See rules 93*a*, 95*a*, and 95*b*.)

"Available" in this rule means ordinarily within 500 feet for stations.

The protective grounding of electrical circuits and equipment to water-pipe systems in accordance with these rules should always be permitted, since such grounding offers the most efficient protection to life and property and is not injurious to the piping systems.

(*b*) ALTERNATE METHODS.—Where underground metallic piping systems are not available, other methods which will secure the desired permanence and conductance may be permitted. In many cases metal well casings, local metal drain pipes, and similar buried metal structures of considerable extent will be available and may be used in lieu of extended buried water-piping systems.

In some cases ground connection may be made to the steel frame of a building containing the grounded circuits or equipment, to which frames of machines and other noncurrent-carrying surfaces should also then be connected. In such cases the building frame should be itself well grounded by effective connection to the ground. This may require artificial grounding for steel frame buildings supported on masonry or concrete (unreinforced) footings.

(*c*) ARTIFICIAL GROUNDS.—When resort must be had to artificial grounds, their number should be determined by the following requirements:

1. Not more than one such ground is required for lightning arresters, except when for large current capacity. At least two grounds are required for low-voltage alternating-current distribution circuits at transformers or elsewhere.

2. Where no part of the circuit or equipment protected can be reached by persons while they are standing on the ground or damp floors, or by persons while touching any metallic piping to which the ground wire is not effectively connected a single artificial ground may be used even if its resistance exceeds that specified in

rule 96. In such cases it is desirable to provide guards for the ground conductor in accordance with rule 93*c* wherever it is otherwise accessible, or to provide insulating mats or platforms so located that persons can not readily touch the ground conductor without standing on such mats or platforms.

(*d*) GROUNDS TO RAILWAY RETURNS.—Protective ground connections should not be made to railway negative return circuits when other effective means of grounding are available, except ground connections from electric railway lightning arresters.

When ground connections are of necessity made to the grounded track return of electric railways, they shall be made in such a manner as not to afford a metallic connection (as indirectly through a grounded neutral with multiple grounds) between the railway return and other grounded conducting bodies (such as buried piping and cable sheaths).

This rule does not prohibit the making of drainage connections (which are not protective grounds) between piping systems and railway negative return circuits for the prevention of electrolysis.

Multiple protective ground connections from other circuits to railway returns should be avoided, and where multiple artificial grounds are made on such other circuits near such railway returns, they should be so arranged as to prevent the flow of any considerable current in and between such connections, thus reducing their effectiveness or causing other damage.

95. Method.

(*a*) Ground connections to metallic piping systems should be made (except as permitted in *b*) on the street side of water meters, which might interrupt the continuity of the underground metallic pipe systems, but connections may be made immediately inside building walls to secure accessibility for inspection and test. When water meters are located outside buildings or in concrete pits within buildings where piping connections are imbedded in concrete flooring, the ground connection may be made on the building side of the meters, if they are suitably shunted.

(*b*) When the making of a ground to a piping system outside meter or other device would involve a long run, connection for equipment or wire runways (but not for circuits) may be made to the water-piping system at a point near the part to be protected, provided there are no insulating joints in the pipe to prevent a good ground. In such cases care should be taken to electrically connect all parts of the piping system liable to create a hazard (if they become alive) and to shunt the pipe system where necessary around meters, etc., in order to keep the connection with the underground piping system continuous.

Gas-piping systems within buildings should not be used for purposes of this rule, except that gas piping need not be insulated from otherwise well-grounded electrical fixtures and where the making of another ground connection for a fixture would involve a long run and the fixture is therefore, of course, not within reach of plumbing or plumbing fixtures, the gas piping may for small fixtures be utilized as the sole ground connection. Where so used the gas-piping and water-piping systems within the building shall be grounded at their points of entrance. (See rule 93*a* and 94*a*.)

(*c*) The ground connection to metallic piping systems should be made by sweating the ground wire into a lug attached to an approved clamp and firmly bolting the clamp to the pipe, after all rust and scale have been removed, or by soldering the ground connection into a brass plug which has been tightly screwed into a pipe fitting, or, where the pipe is of sufficient thickness, screwed into a hole in the pipe itself, or connection may be made by other equivalent means. The point of connection should be as readily accessible as possible, and the position should be recorded.

With bell and spigot joint pipe it may be necessary to connect to several lengths where circuits or equipment of large current-carrying capacity are being grounded.

(*d*) Artificial grounds should be located where practicable below permanent moisture level, or failing this at least 6 feet deep. Each ground should present not less than 2 square feet surface to the soil. Areas where ground water level is close to the surface should be used when available.

96. Ground Resistance.

(*a*) LIMITS.—It is recommended that the combined resistance of the ground wires and connections of any grounded circuit, equipment, or lightning arrester should not exceed the values given below, if ground connections made according to rule 94 will sufficiently limit the resistance.

It will frequently be impracticable with artificial grounds to obtain resistances in dry or other high resistance soils as low as the values given below for ordinary soils. In such cases use two grounds as defined in rule 95*d*, and no requirement will be made as to resistance. (See also rule 94*c*–2.)

The current stated opposite the different resistances in the table is either the current capacity of a circuit from which leakage can occur to the grounded circuit, or the continuous current capacity to which the grounded equipment or arrester is limited by design or by automatic cut-outs.

Where a secondary is exposed only through transformer windings, this current capacity will be that of the primary fuse of the transformer. Where the secondary is exposed by the conductors of conflicting or crossing high voltage circuits, the current capacities will be those of the automatic cut-outs in such circuits.

Amperes	Water-pipe grounds	Artificial grounds, ordinary soils
	Ohms	*Ohms*
Less than 10	15	25
Ten to 25	6	25
Twenty-five and above	3 or less	25

The product of the corresponding numbers in the first and second columns is never greater than 150 volts—that is, the potential difference due to the stated current is never greater than 150 volts—where connections are made to water pipes.

Where more than one ground is made on the same circuit, equipment, or arrester in the same vicinity, all such grounds are considered collectively in respect to meeting the requirements of this rule.

(*b*) CHECKING.—The resistance of station grounds should be checked when made. With artificial grounds this check may be made by measuring the voltage between the grounded point of the circuit, or the grounded frame of the equipment or the grounded point of the lightning arrester and an auxiliary metal reference rod or pipe driven into the ground, while a measured current is flowing through the ground connection and any exposed metal piping or other artificial ground in the vicinity, but not within 20 feet.

If the station ground is to water piping, the check may be made with current flowing through the water piping and some independent piping system or artificial ground in the vicinity, but not within 20 feet.

The auxiliary rod or pipe should be at least 10 feet from any artificial ground or piping systems through which the measured current is made to flow.

All ground connections shall be inspected periodically.

Ground connections on distribution circuits should, when installed, be tested for resistance unless multiple grounding to water-piping systems is used.

97. Joint Use of Grounds and Ground Conductors for Different Systems.

(*a*) GROUND CONDUCTORS.—Ground conductors should be run separately to the ground (or to a sufficiently heavy grounding bus or system ground cable which is well

connected to ground at more than one place) from equipment and circuits of each of the following classes:

1. Lightning arresters.
2. Secondaries connected to low-voltage lighting or power circuits.
3. Secondaries of current and potential transformers and cases of instruments on these secondaries.
4. Frames of direct-current railway equipment and of equipment operating in excess of 750 volts.
5. Frames of utilization equipment or wire runways other than covered by item 4.

(*b*) GROUNDS.—Lightning-arrester ground connections shall not be made to the same artificial ground (driven pipes or buried plates) as circuits or equipment, but should be well spaced and, where practicable, at least 20 feet from other artificial grounds.

Appendix III.—DERIVATION OF FORMULA FOR THE RESISTANCE OF A GROUND CONNECTION

Let (1) and (2), Fig. 38, be two metallic bodies embedded at a distance from each other in an infinitely extended semiconducting medium like the earth. Let it be supposed that body (1) is continuously maintained at a potential $+V_1$ and body (2) at a potential $-V_2$. The difference of potential between (1) and (2) will be $V=V_1+V_2$. A current I will flow from (1) to (2) through the medium, which offers a resistance R. Accompanying the difference of potential V between (1) and (2) there will be an electric intensity E at all points in the medium, which will correspond to a charge of static electricity $+Q$ on body (1) and $-Q$ on (2). Suppose a closed surface S of any form to be drawn about (1) but not including (2).

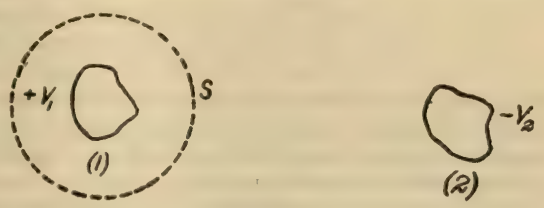

FIG. 38

Let ds be an element of area of this surface,
n, the direction normal to the surface,
E_n, the normal component of the electric intensity at any point on the surface,
i_n, the normal component of the current density at any point on the surface,
K, the dielectric constant of the medium, and
ρ, its resistivity.

By Gauss's theorem $\int\int E_n ds=\frac{4\pi}{K}Q$. Also $-\frac{\delta V}{\delta n}=E_n$.

By Ohm's law $-\frac{\delta V}{\delta n}\,dn=i_n ds \bullet \rho\frac{dn}{ds}=E_n dn$, or

$\rho i_n ds=E_n ds$. Integrating $\rho\int\int i_n ds=\int\int E_n ds$.

$$\therefore \rho I=\frac{4\pi}{K}Q. \qquad (a)$$

Now $Q=C_1V$, where $\frac{K}{C_1}$ is the electrostatic capacity between bodies (1) and (2), and by Ohm's law, $I=V/R$.

Substituting for I and Q in equation (a), therefore,

$\rho=\frac{4\pi}{K} C_1R=4\pi CR$, where C is the electrostatic capacity between (1) and (2) in medium of dielectric constant equal to unity, supposing the relative positions of the bodies to be the same.

Hence, the resistance $R=\rho/4\pi C$.

It is obvious that this formula applies to either two bodies or one; that is, either to a case where current flows from one body to another, or to a case where current flows from a single body toward infinity; depending upon whether C is calculated for the condenser formed by the two oppositely charged bodies or for a single body in free space. To clear up this last statement it is only necessary to consider that (2) is a shell inclosing (1) and infinitely large. In this case V_2 becomes equal to zero, $V_1=V$, and the electrostatic capacity C becomes that of (1) in free space; consequently R is made to refer to (1) only, and the current I is supposed to flow away from (1) toward infinity. It is also evident that it is immaterial whether body (1) is a single conductor or several separate conductors, as long as the surface S incloses all of them, except that in calculating C and R all of the electrodes inclosed by the surface S should be treated as a single electrode.

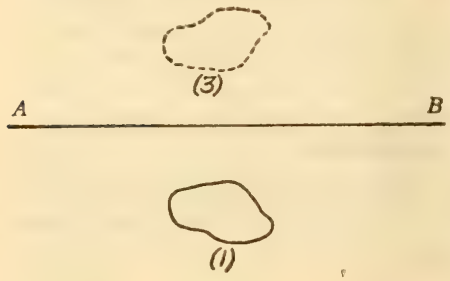

FIG. 39

The formula just derived can be used to find the resistance offered to flow of current either away from a single electrode buried in the earth, or from one electrode to another, these electrodes being of any shape whatever, if the value of C and the resistivity of the soil are known. Where a single electrode is concerned, refer to Fig. 39. Here A B is a plane passing through the medium described above, while (3) is the image of the electrode (1) above the plane. With (1) and (3) at the same potential, and current flowing away from both of them toward infinity, the electric field will be symmetrical with respect to the plane A B in accordance with the law of images. The resistance to current flow will be $R=\rho/4\pi C$, since, as stated above, it makes no difference whether the electrode inclosed by S is composed of a single conductor or several separate conductors. Now, the electric fields being symmetrical, the half of the medium above the plane may be imagined to be removed without disturbing the field in the other half. The remainder may then be taken as representing the earth, the plane A B forming the surface, because for practical purposes it may be assumed that the earth is a semi-infinitely extended conducting medium. With the upper half of the medium removed the formula becomes $R=\rho/2\pi C$, for the reason that the resistance is then twice as great as before, R referring to the resistance to flow of current away from (1), while C refers to the combined electrostatic capacity in free space of (1) and (3).

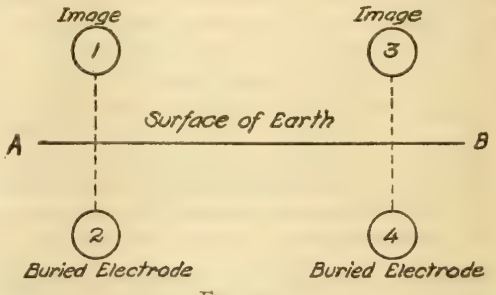

FIG. 40

Where two electrodes are concerned refer to Fig. 40. Here, *A B* is a plane passing through the medium as above, while (1) and (3) are the respective images of the electrodes (2) and (4) above the plane. With (1) and (2), and (3) and (4), respectively, at the same potential, and current flowing from (1) to (3) and also from (2) to (4), the electric field will be symmetrical with respect to *A B*. The resistance to flow of current will be $R=\rho/4\pi C$. Now, as in the preceding paragraph, the half of the medium above *A B* may be imagined to be removed without disturbing the field in the other half, and the remainder taken as representing the earth. With the upper half of the medium removed the resistance becomes $R=\rho/2\pi C$ as before, *R* referring to resistance to flow of current from (2) to (4) and *C* to the electrostatic capacity of the condenser formed by electrode (2) and its image (1), on the one hand, and electrode (4) and its image (3) on the other.

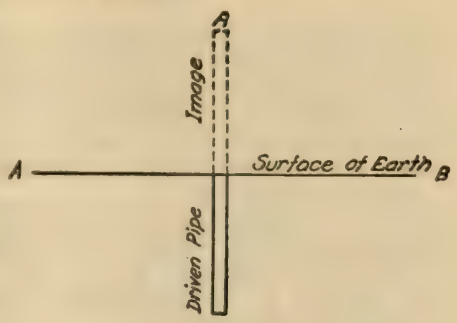

FIG. 41

To fix the ideas in regard to the capacity *C*, it may be considered that in Fig. 39 the capacity is that of (1) and (3) in free space when they are connected together by a fine wire, thus making a single conductor of them. In Fig. 40 the capacity is that between the conductors formed by connecting from (1) to (2) and from (3) to (4) with fine wires.

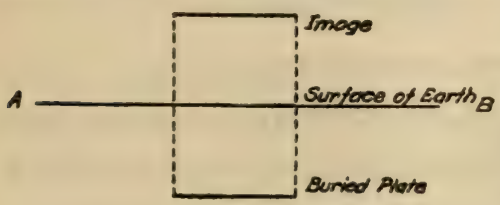

FIG. 42

The images in the cases of some of the forms of electrodes used in practice would be as follows: For a driven pipe, another pipe of the same size and length extending above the plane *A B* as in Fig. 41. For a plate, another plate of the same size situated in the same relative position above the plane *A B*, that the other is below as in Fig. 42.

In calculating *C* for the pipe the nearest approximation that can be made is that obtained by considering it an ellipsoid of revolution. The formula for the electrostatic capacity in free space of an ellipsoid of revolution of which the length of the major axis is great in comparison with that of the minor axis is $C=L/2 \log_e \frac{2L}{d}$ where *L* is the length of the major axis and *d* of the minor axis. That is, *L* would be twice the length of the driven pipe and *d* its external diameter. There appear to be no available formulæ for other forms of electrodes.

With regard to ρ perhaps an explanation should be given of the use of this term which has been applied to soils in much the same sense as it is usually applied to metals. This application is not exactly rigorous because of the fact that the resistivity of soils is not as nearly continuous in the mathematical sense as is the resistivity of metals. That is to say, soil is made up of particles of insulating substances of various kinds such as quartz, mica, and the like, with the spaces between the particles filled to a greater or less extent with a water solution which is an electrolytic conductor. In passing from point to point in the earth, therefore, the resistivity may jump from very low values for points in the solution to extremely high values for points in the particles of mica and quartz. Hence, in speaking of the resistivity of the earth at a point the value actually meant is the average of that of a relatively large

volume in the vicinity of the point; and in speaking of earth of uniform resistivity it is meant that this average resistivity is uniform throughout the entire volume.

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